ELECTROSTIMULATION THERAPY AND SELECTIVE POSTERIOR RHIZOTOMY IN THE TREATMENT OF CHILDREN WITH CEREBRAL PALSY

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Academic Dissertation

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1. LIST OF ORIGINAL PUBLICATIONS

This thesis is based on following publications, which will be referred to in the text by their Roman numerals I-IV

I. Mäenpää H, Salokorpi T, Jaakkola R, Blomstedt G, Sainio K, Merikanto J, von Wendt L: Follow-Up of Children with Cerebral Palsy after Selective Posterior Rhizotomy with Intensive Physiotherapy or Physiotherapy Alone. Neuropediatrics 2003; Vol 34: 67-71.

II. Mäenpää H, Jaakkola R, Sandström M, von Wendt L: Effect of Sensory-Level Electrical Stimulation of the Tibialis Anterior Muscle during Physical Therapy on Active Dorsiflexion of the Ankle of the Children with Cerebral Palsy. Pediatr Phys Ther 2004; 16:39-44.

III Mäenpää H, Jaakkola R, Taimo A, Sandström M, von Wendt L: Electrostimulation at sensory level improves function of the upper extremities in children with cerebral palsy: a pilot study. Dev Med Child Neurol 2004; 46:84-90.

IV Mäenpää H, Jaakkola R, Sandström M, von Wendt L: Does Microcurrent stimulation increase the range of movement of ankle dorsiflexion in children with cerebral palsy? Disab Rehabil 2004; vol. 26, No 11:669-677.

2. ABBREVIATIONS

AC	Alternating current
Ach	Acetylcholine
AP	Action potential
BPD	Bronchopulmonary dysplasia
BTX-A	Botulinum toxin A
CNS	Central nervous system
CP	Cerebral palsy
CPGs	Central pattern generators
CITB	Continuous intrathecal baclofen
CS	Corticospinal
DC	Direct current
DCD	Developmental coordination disorder
DST	Dynamic system theory
ELBW	Extremely low birth weight
EMG	Electromyography
EPSP	Excitatory post synaptic potential
ES	Electrical stimulation
FES	Functional electrical stimulation
GM	General movements
GMFCS	Gross motor function classification scale
GMFM	Gross motor function measurement
Hz	Hertz – cycles per second
I	Current
LBW	Low birth weight (BW < 2500g, or in some references < 2000g)
mA	Milliamperes
MENS	Microcurrent electrostimulation
MND	Minor neurological disorder / dysfunction
MRI	Magnetic resonance imaging
µsec	microsecond
NDT	Neurodevelopmental therapy
NGST	Neuronal group selection theory
NICU	Neonatal intensive care unit
NMES	Neuromuscular electrical stimulation
PD	Pulse duration
PhD	Phase duration
PCI	Pysiological cost index
PT	Physiotherapy
pps	Pulse per second
PVL	Periventricular leukomalacia
R	Resistance
ROM	Range of motion
SA	Sensorymotor approaches
SI	Sensory integration
SIPT	Sensory integration and praxis test
SPR	Selective posterior rhizotomy
TENS	Transcutaneous electrical nerve stimulation
TES	Threshold electrostimulation
TMS	Transcranial magnetic stimulation
US	Ultrasound
V	Voltage
VLBW	Very low birth weight (BW < 1500 g)
Z	Impedance

3. ABSTRACT

Cerebral palsy (CP) is a persistent but not unchanging disorder of movement and posture, appearing early in life and caused by a non-progressive lesion of the developing brain. During the last century, knowledge of the mechanisms controlling the functions of the CNS increased rapidly as sophisticated physiological, neurochemical and imaging techniques were developed. Motor behaviour is no longer explained in terms of reflex mechanisms. Motility is nowadays regarded as the net result of the activity of complex spinal or brainstem machineries, which are subtly modulated by segmental afferent information and controlled by supraspinal networks.

Children with early acquired motor deficits often have difficulty producing selective movements in an affected extremity. It has been suggested that this is due to some form of developmental apraxia caused by defective motor planning in early infancy. CP is treated by means of PT, orthopaedic surgery, pharmacotherapy and orthoses. These therapies have been based on the contemporary understanding of neuronal mechanisms.

The aim of this study was to investigate the impact of new rehabilitation methods: selective posterior rhizotomy (SPR) and neuromuscular electrostimulation (NMES) at sensory level and microcurrent therapy (MENS) in children with CP. The design was a series of open studies and the ES studies were uncontrolled.

The SPR series consisted of 42 children with CP (21 operated plus PT and 21 PT only). Children in the groups of SPR and intensive PT experienced steady development during the five-year follow-up period and no significant differences were observed in the mean functional scores between the groups. Although we failed to demonstrate any additional effect of SPR on motor development in children with spastic CP as a group, SPR appeared to contribute to a resumption of motor development in children with arrested motor development.

In the lower limb (tibialis anterior) NMES study there were a total of 17 children with CP. The children were re-assessed at two and nine months after cessation of NMES. Using NMES at sensory level during a four week period the children with CP developed new, active, selective muscular movements and stability in their lower extremity (dorsiflexion, inversion-eversion and toe flexion-extension) for nine months after the cessation of therapy.

In the upper limb NMES study, there were a total of 12 children. Two muscle groups were stimulated (infraspinatus and dorsiflexors) during five weeks in addition to physio- and/or occupational therapy. There were two subgroups: children < 4 years of age and children > 4 years of age and older and we compared the results. Hand function improved in both age groups in response to sensory level electrical stimulation. In addition children found and mastered the desired movement. This observation supports the fact that motor learning occurred.

In the study with MENS the group consisted of 12 hemiplegic children with persistent equinus. The MENS was administered to the gastrocnemius muscle for four weeks, 30-60 min/day. The treatment took place at home. The results showed 10-15 degrees of passive range of motion (ROM) relief of ankle contracture.

It was concluded that NMES appears to produce sensory feedback from limbs by activating the spinal and supraspinal tracts and cortical body schema areas which are needed to produce voluntary movement. The ability to move the limbs in turn increases the activity of the children during the therapy sessions.

MENS therapy as an add-on treatment produced at least temporary relief of the myocontracture of the Achilles tendon in children with CP. The gained increase in ROM can postpone the surgical elongation of the Achilles tendon for years.

The definite place of ES therapy in children with CP can be judged only after controlled trials.

4. INTRODUCTION

During the last century, knowledge of the mechanisms governing the functions of the CNS increased rapidly as sophisticated physiological, neurochemical and imaging techniques were developed. Motor behaviour is no longer explained in terms of reflex mechanisms (Sherrington 1906, Hadders-Algra 2000a,b). Motility is nowadays regarded as the net result of the activity of complex spinal or brain stem machineries, which are subtly modulated by segmental afferent information and ingeniously controlled by supraspinal networks (Grillner et al. 1995, Hadders-Algra 2000b).

Deficient postural control is one of the main factors in motor disorders such as CP and developmental co-ordination disorder (DCD), disorders which from early childhood seriously interfere with the quality of life. The abnormalities in postural control might be due to early deviations in the development of the CNS or to insults in the perinatal period or later, leading to deficiencies in the processing of sensory information and motor output.

CP is a heterogeneous group of persistent disorders of movement and posture caused by non-progressive defects or lesions of the immature brain (Aneja 2004). When defined in this way CP can be understood as a disorder of motor control.

According to the systems theory approach, motor control includes more aspects than the simple control of posture and movement (Thelen 1995). Systems' theory argues that movement emerges from an interaction between the individual, the task and the environment where the task is carried out. As a result, movement is not solely the result of muscle-specific motor programmes or stereotyped reflexes, but results from a dynamic interplay between perceptual, cognitive and action systems. It has also been suggested that the CNS contains internal models, which represent internal representation of one's own body and its interaction with the external world, in order to optimise motor control and learning (Blakemore et al. 2002). Action systems are defined as including both the neuromuscular aspects and the physical and dynamic properties of the actual musculoskeletal system. It must be realised that the nervous and musculoskeletal systems cannot be separated. They interact with each other to meet the demands of both the internal and external environment. It is therefore important to approach the analysis of a person with movement disorders with a balanced view of the neural control of movement, the biomechanical requirements for a task and the limitations the CNS damage imposes on both of these systems.

Since the late 19th century, CP has been treated using PT, orthopaedic surgery and orthoses. These therapies have been based on the contemporary understanding of neuronal mechanisms. During the last decades a number of new therapeutic approaches have started to emerge, partly as a result of new insights into neuromotor regulation. Selective posterior rhizotomy (SPR) was presented in 1888 by Abbe (see Fasano et al. 1978) and was further developed by Fasano (Fasano et al. 1978). Peacock and his co-workers reintroduced SPR in the 1980s (Peacock and Arens 1982).

Electrostimulation also re-emerged as a theoretical tool in CP and related disorders. Today, the theoretical rehabilitation modalities of CP are diverse, and the optimal utilisation of the different methods awaits conclusive studies. In this thesis, the way SPR and NMES act at sensory level and the action of MENS are evaluated on the basis of a series of open studies.

5. REVIEW OF THE LITERATURE

5.1. Cerebral palsy

Cerebral palsy (CP) is a term of convenience applied to a group of motor disorders of central origin defined by a clinical description. It is a symptom complex, not a specific disease. It was defined in 1959 in the Little Club paper as "a persistent though not unchanging disorder of movement and posture, appearing early in life and due to a non-progressive lesion of the developing brain" (MacKeith et al. 1959). A more recent definition was "an umbrella term covering a group of non progressive, but often changing, motor impairment syndromes secondary to lesions or anomalies of the brain arising in the early stages of its development" (Mutch and Alberman 1992).

5.1.1 Incidence

For children born in the mid 1960s in Finland the incidence was reported to be 4.6/ 1000 (von Wendt et al. 1985). According to the latest Finnish report by Lano in 2002 in Finland the incidence was 2.2/1000 live-born children (Lano 2002). In this study, CP was defined in accordance with the prevailing general recommendations and it was shown that the incidence is of the same magnitude (2-2.5 of every 1000 live-born children) in the western world. (Stanley et al. 2000). In the most recent survey, the surveillance of cerebral palsy in Europe (SCPE) the incidence is 2.08/1000 live born children (Cans et al. 2000). The latest Swedish population-based CP report comprises children born in 1991-94. The live-birth prevalence was 2.12 per 1000. The live-birth prevalence for CP in the birth year period 1991-94 continued to decrease slightly (Hagberg et al. 2001).

A trend towards increasing CP rates with decreasing birth-weights has been observed in many previous studies (Olsen et al.1997, Pharoah et al. 1998, Stanley et al. 2000). Olsen et al. (1997) found a 9.5 % incidence of CP in low birth weight children (LBW, birth weight< 2500 g) in Finland whereas the incidences in very low birth weight (VLBW, birth weigh< 1500g) varied in different countries from the lowest value of 5.4 % in Sweden to the highest reported value of 18 % in Finland (Ikonen et al. 1992, Hagberg et al. 1996, Olsen et al. 1997). In a study report by Salokorpi et al. the incidence of CP in extremely low birth weigh infants (ELBW, birth weight< 1000g) was 19 % of the children born in 1990-1994 (Salokorpi 1999).

5.1.2 Etiology

CP has a complex and multifactorial etiology. Approximately 10 % of cases can be ascribed to perinatal hypoxia, but the vast majority of cases are caused by the interplay of several risk factors and antenatal, perinatal, and postnatal events. The strongest risk factors are obviously a premature birth and a low birth weight (Lawson and Badawi 2003). Apart from gestational age, periventricular leukomalacia (PVL), bronchopulmonary dysplasia (BPD) and hypotension in preterm infants are major factors when it comes to neurological morbidity at term (Martens et al. 2003). Multiple-birth infants run a four times higher risk of developing CP than singletons, mainly as a result of the higher risk of preterm birth in multiples (Topp et al. 2004). Brain malformations are one of the major causes of CP, although the exact frequency is unknown (Aicardi 1998). Otherwise genetic factors do not commonly play a role in the causation of CP, with the exception of ataxic forms (Aicardi 1998, Hagberg et al. 2001).

According to the study by Zupan et al. (1996), in which they studied a cohort of 753 very preterm infants born at 24 to 32 weeks of gestation, 69 (9.2%) of the infants had a diagnosis of cystic PVL. The highest PLV frequency was observed among the infants born at 28 weeks (16%). Inflammatory prenatal events occurring during the last days or weeks before delivery and PVL occurrence were strongly associated. The combination of intra-uterine infection and premature rupture of membranes was associated with a very high risk (22%) of CP. In contrast, chronic fetal

distress, such as severe intra-uterine growth retardation and pre-eclampsia, was seldom followed by PVL (2%) (Zupan et al. 1996).

CP with a post-neonatal origin (arising more than 28 days after birth, but before the age of 25 months), was examined by Cans and coworkers in children born between 1976-90 and the authors found that infection accounted for 50 %, vascular episodes for 20 % and head injury for 18 % of the cases (Cans et al. 2004). There are some other risk factors identified such as maternal diabetes mellitus, threatened abortion, pre-eclampsia and chorionamnionitis (Aicardi 1998, Wu et al. 2003).

5.1.3 Classification

CP is classified most often according to the predominant movement abnormality, spasticity, dystonia, athetosis and ataxic features, and grouped by the affected extremities (monoplegia, diplegia, triplegia, hemiplegia, and quadriplegia) (Cans et al. 2000) (**Table 1)**.

Table 1. European classification of (motor impairment in) CP (Cans et al. 2000)

Spastic cerebral palsy is characterised by at least two of
- -Abnormal movement pattern of posture or movement
- -Increased tone (not necessarily constant)
- -Pathological reflexes (increased reflexes, hyperreflexia, or pyramidal signs- such as the positive Babinski response)

Spastic bilateral cerebral palsy is diagnosed if
- -Limbs on both sides of the body are involved

Spastic unilateral cerebral palsy is diagnosed if
- -Limbs on one side of the body are involved

Ataxic cerebral palsy is characterised by both
- -Abnormal pattern of posture and/or movement
- -Loss of orderly muscular coordination so that movements are performed with abnormal force, rhythm, and accuracy

Dyskinetic cerebral palsy is dominated by both
- -Abnormal pattern of posture or movement
- -Involuntary, uncontrolled, recurring, and occasionally stereotyped movements

Dystonic cerebral palsy is dominated by both
- -Hypokinesia (reduced activity <-> stiff movement)
- -Hypertonia (tone usually increased)

Choreoathetotic cerebral palsy is dominated by both
- -Hyperkinesia (increased activity <-> stormy movement)
- -Hypotonia (tone usually reduced)

Diplegic and hemiplegic syndromes have been found to account for one-third to almost half of all CP syndromes (Hagberg et al. 1996, Pharoah et al. 1998). Diplegia was present in 80 % of extremely preterm, 66 % of very preterm, 58 % of moderately preterm, and 29 % of the term group with CP (Hagberg et al. 1996). Hemiplegia was most common among term infants. In the Swedish study by Hagberg et al. in 2001 spastic hemiplegic, diplegic and tetraplegic subtypes accounted for 33%, 44% and 6% respectively, while dyskinetic CP and simple ataxia accounted for 4% of the cases (Hagberg et al. 2001).

According to Hadders-Algra and Touwen (2001), there are two groups of motor disorders which are attributed to a lesion of the brain at an early age: CP and clumsiness. Clumsy children are nowadays classified according to DSM-IV as Developmental Coordination Disorder (DCD), a term

which generally denotes children who have such poor motor co-ordination that it affects daily activities at home and at school, notwithstanding the presence of a normal intelligence and the absence of evident neurological pathology (American Psychiatric Association, 1994). In children with DCD, the connection between structural abnormalities of the brain and motor dysfunction is somewht ambiguous (Hadders-Algra and Gramsbergen 2001). Recently Hadders-Algra and Touwen (2001) argued that the indications of pre- and perinatal brain damage can be found in one-third of children with minor motor dysfunctions. The motor disorder in the latter group of children could be regarded as a borderline form of CP (Hadders-Algra and Touwen 2001), but is currently rarely identified as such.

According to the Surveillance of CP in Europe, total of 4792 children with CP were born in 1980-90 in 14 different centres, and the classification of CP can be seen in **Table 2** (Cans 2000).

Table 2. The prevalence of different subtypes of CP

Hemiplegic	29.2 %
Bilateral spasticity	54.9 %
Dyskinetic	6.9 %
Ataxic	4.3 %
Unclassified	3.7 %

5.1.4 Prognosis

The outcome after brain damage acquired in the pre-, peri-, or postnatal period is heterogeneous. Some children recover completely, whereas others suffer from severely handicapping conditions (Costello et al 1988, Ford et al. 1989). The developmental levels are related to some extent to the size and location of the lesion and the timing of the insult. The size of the lesions predicts outcome best (Hadders-Algra 2001a, Forssberg 1999a). In line with this Barkovitch et al. (1998) and Haataja et al. (2001) demonstrated that very severe basal ganglia, subcortical or diffuse white matter lesions were always associated with a poor neurological outcome. In preterm infants, it has been reported that frontally located lesions are associated with better outcomes than those located occipitally or parietally (Fawer and Calame 1994, Fazzi et al. 1994). Lesions acquired before the age of 36 gestational weeks typically occur in the periventricular regions, whereas lesions acquired around term are generally located in the cortical (subcortical) areas and/or in the thalamus, in the basal ganglia and in the brain stem (Volpe 1994).

In the study by de Vries et al. (1993), the correlation between the degree of PVL grades I-IV diagnosed using cranial ultrasound and MRI later in infancy was evaluated in children with CP. In the study, the reported risk of CP was 9% in grade I, 11% in grade II, 36 % in grade III, and 76% in grade IV (de Vries et al. 1993).

Boardman et al. 2005, compared MRI correlates of hemiparesis after neonatal (cerebral infarction occurring within 28 days of birth, 28 patients) with middle cerebral artery stroke in childhood (28 days to 18 years, 43 patients). Hemiparesis was more common after childhood-onset ischemic stroke (56%) than after neonatal ischemic stroke (24%). In neonatal ischemic stroke concomitant involvement of basal ganglia, cerebral cortex, and posterior limb of the internal capsule predicted the development of hemiparesis. Thus, no child with only one or two of these structures involved developed hemiparesis. In contrast, in childhood-onset ischemic stroke, concomitant basal ganglia, cerebral cortex, and posterior limb of internal capsule lesions tended to

be associated with hemiparesis (9 out of 11), but this adverse outcome was seen also among patients with involvement of one or two sites (Boardman et al. 2005).

5.2 Normal development of central nervous system (CNS) and the deviation in CP

During the past 20 years research has increasingly documented the constraints on the performance of voluntary skills observed in children with CP. Lesions of cortical sensomotor areas and the thalamus/basal ganglia during the fetal or neonatal period give rise to CP (Forssberg 1999a), which describes a group of clinical syndromes encompassing various combinations of movement disorders **(Table 3)**.

Table 3. Movement disorders constituting CP (Forssberg 1999a)

Spasticity
Muscular malformations
Dyskinesia (dystonia, athetosis, chorea, ataxia)
Retained transient infant reactions
Paresis
Central dyscoordination

According to Forsberg (1999a) CP is an umbrella diagnosis for several different clinical conditions accommodating the movement disorders listed in the table 3. The clinical picture varies in different subjects. Depending on the predominant symptom, the syndromes are called "spastic" or "dyskinetic" CP. Some of the motor difficulties in CP are attributable to the lack of development of proper neural control mechanisms (Forssberg 1999a).

Researchers have been studying motor development since the early part of the last century. In general, we know that infants usually crawl before they walk and display stable postural control while sitting before they control their posture when standing upright. We know that myelination and neural transmission increases, visual acuity and depth perception improve, and flexor and extensor dominance of agonist and antagonist muscle groups shifts over the first year of life (Miller 2005).

The acquisition of skilled motor actions depends on the development of the brain. What is normal, abnormal or delayed depends on the sequencing and timing of the various phases of brain development (Brown et al. 1997).

The development of mobility begins early in the antenatal period, the first movements being evident by eight weeks of gestation. As the fetus develops, the complexity of movements, in both kinematic and neurological aspects, increases. The combination of balance and motility is the foundation on which later postural skills are based (Brown et al. 1997).

5.2.1 Fetal and neonatal movements

The very first movements seen in any fetus are slow extensions of the neck at 7-7.5 weeks. They are present for a few days and are then followed by the occurrence of startles and general movements (de Vries et al. 1982, Prechtl 1997). After the ninth gestational week, the repertoire expands rapidly. This is remarkable in two respects. First, the young fetus is able to perform isolated movements of one limb at an age when one would expect a longer period of diffuse and generalised motor activity. The second is the unexpected finding of the simultaneous onset of arm and leg movements, unexpected because of the long-held principle of cephalocaudal development in spinal motor function (Prechtl 1997). Between 10.5 and 12 weeks the fetus starts to make breathing movements. These are rhythmic contractions of the diaphragm, usually in a series of several movements, although they may also occur in isolation (Prechtl 1997).

At 11 weeks, three new patterns appear - the opening of the jaw, the bending forward of the head and complex stretching movements. At 13 weeks, rhythmic sucking movements, often followed by swallowing, occur in bursts. The rate of these sucking movements at 14 weeks is already about the same as in term infants during breastfeeding. Rolling eye movements appear at 16-18 weeks and are followed by rapid eye movements at 20-22 weeks, which also include nystagmoid movements. During the second half of pregnancy, hardly any new movement patterns emerge (Brown et al. 1997, Einspieler et al. 2004).

The rich repertoire of different distinct fetal movement patterns raises the question of their meaning and function. Many fetal movement patterns continue virtually unchanged in form and shape after birth. This must be seen as an adaptive mechanism, ensuring the proper development of the organism and especially of the nervous system and its function after birth (Prechtl 1997, Einspieler et al. 2004).

At birth, a newborn infant has transient movement patterns, such as stepping, postural and righting reactions and general movements which emerged at the fetal stage. It is likely that these innate fetal and infantile movements are generated by similar types of epigenetic central network (Grillner et al. 1995, Forsberg 1999a, Einspieler et al. 2004).

5.2.2 Central pattern generators (CPGs)

It is generally accepted that locomotion and other rhythmic motor behaviours such as feeding and respiration in mammals are based on the activity of spinal functional networks generating the rhythm and shaping the pattern of bursts of motoneurons (Forssberg et al. 1980, Grillner 1985). These basically innate networks are called CPGs, which are capable producing the most co-ordinated motor patterns which require afferent and supraspinal input (Grillner 1985, Forssberg and Dietz 1997). In humans, the best evidence of the existence of CPGs comes from newborns, in whom descending supraspinal control is not yet fully developed. Infant stepping occurs in the near absence of mature corticospinal connections, and is spontaneously initiated or triggered by peripheral stimuli (Zehr and Duysens 2004). In addition, it is known that in persons with complete or incomplete paraplegia, due to a spinal cord injury, locomotor EMG activity and movements can be both elicited and trained (Dietz 1997). It therefore appears to be evident that CPGs are active controllers of human rhythmic movements.

In the case of the cat, it is assumed that there is at least one CPG for each limb and in humans there could be separate CPGs for arms and legs on each side (Dietz 2003, Zehr and Duysens 2004). According to Delwaide and coworkers (1977), proprioceptional connections could link rhythmic movement and reflexes between the upper and lower limbs.

5.2.3 Regulation of locomotor CPGs

The fine regulation of rhythmic human movements typified by locomotion can be understood as the sublime interaction of a tripartite system consisting of supraspinal input, spinal central pattern generating circuits (CPG), and sensory feedback (Zehr and Duysens 2004). Animal models of the supraspinal locomotor executing system are based on pathways originating from the midbrain locomotor region which is under the control of the cerebral cortex and basal ganglia. They are needed for volitional control, the planning, initiation and execution of movements and motor learning (Takakusaki et al. 2004, Kandel et al. 1995). Two major pathways descend from the midbrain, the medullary reticulospinal tract and the pontomedullary locomotor strip. These descending commands delegate the motor command for rhythmic movement to the CPG networks controlling the arms and legs (Takakusaki et al. 2004, Zehr and Duysens2004).

The cerebellum, in turn receives efferent copies of CPG output to motor neurons from the motor cortex as well as information about the activity of the peripheral motor apparatus. The

cerebellum influences motoneurons indirectly via vestibulospinal, rubrospinal, reticulospinal and corticospinal pathways (Arshavsky et al. 1984). Despite its comparatively consistent anatomical structure and simple circuitry, the actual role of the cerebellum in locomotor control remains somewhat elusive. One principal function may be the timing of muscle activation, "fine-tuning" the output by adapting each step cycle (Duysens et al. 2004). On the other hand it is well known that the cerebellum is needed for equilibrium control (Kandel et al. 1995). The animal model of the locomotor executing system is supported by findings related to consequences of lesions of CNS in humans (Dietz and Harkema 2004, Dietz 2003, Duysens et al. 2004). Locomotor movement ensues, and a flood of peripheral feedback arrives at the spinal cord to inform the CNS of local conditions and to help sculpt CPG output (Dietz 2002).

Sensory feedback contributes strongly to the regulation of the basic pattern (CPGs), and together the whole system normally results in seamless, smooth locomotor movement (Zehr and Duysens 2004).

Sensory feedback is also an integral part of the over all motor system and is critical in modifying CPG-generated motor programs in online adaptations to the environment (MacKay-Lyons 2002, Dietz 2003). The control of locomotion involves the use of afferent information from a variety of sources in the visual, vestibular, tactile and proprioceptive systems (Dietz 2003). For example, visual feed-forward information reduces the activity that arises from the length sensors of muscles (the muscle spindles) (Jones 2001).

Pearson identified three potential roles in animals for afferent feedback in the production of rhythmic movements, and all three roles involve the adapting movements to external environments.

1. The first role is that of reinforcing CPG activities, particularly those involving the load-bearing muscles, such as the cat hind-limb extensor muscles during the stance phase of gait.
2. The second role is a timing function whereby the sensory feedback provides information to ensure that motor output is appropriate for the biomechanical state of moving body parts in terms of position, direction of movement and force.
3. The third role is that of facilitating phase transition in rhythmic movements purportedly to ensure that a certain phase of the movement is not initiated until the appropriate biomechanical state has been achieved (Pearson 1993).

While it is easy to identify the role of sensory feedback in locomotion in animal preparations the same thing does not apply in intact humans (Zehr and Duysens 2004). It is, however, possible to study the role of cutaneous afferents of the foot for transition in gait. ES of these afferents elicits reflex responses in many leg muscles. These responses, which have a latency of 70-80 ms, are termed P2 responses. Cutaneous stimulation at the foot elicits the facilitation of the extensors in this instance phase and of the flexors in the swing phase. This phenomenon has been called "phase-dependent reflex reversal". It is functionally appropriate to maintain stability and progression in response to unexpected sensory stimulation during walking. Cutaneous input not only affects CPGs but is also more directly connected to motoneurons through various reflex pathways, which are largely under the control of the CPG (Dietz 2003, Zehr and Duysens 2004).

Another kind of reflex reversal appears when the response changes from facilitation into suppression in a given muscle e.g. the tibialis anterior. In this muscle, a cutaneous stimulus delivered during the swing phase generates the facilitation of the P2. In contrast when the stimulus is applied during the transition from swing to stance, the P2 response is suppressed. It is suggested that tibialis anterior suppression around heel strike is needed to avoid the inadvertent activation of the foot dorsiflexion during the period of step cycle (Duysens et al. 2004).

It seems that at the end stance tactile input from low-threshold beta fibres and spinal CPGs modifies the activity of the tibialis anterior and the end swing is controlled by pyramidal tracts (Duysens et al. 2004).

In contrast to cutaneous reflexes, tibialis anterior stretch reflexes are largely seen during the stance phase. The same thing applies to the soleus muscle, especially during the early part stance. There is growing evidence that group II afferents from muscle spindles are important providing functionally important feedback during the stance phase. During walking, it is estimated that stretch reflexes contribute up to 30 % to 60 % of the activation of the soleus, especially during the early part of stance (Zehr and Duysens 2004). In addition proprioceptors in tendons, as well as mechanoreceptors in the joints convey impulses to the spinal cord during locomotion (Dietz 2002).

Proprioceptive input continuously modulates the programmed pattern of locomotion according to information from peripheral sensors. One of the primary functions of proprioceptors is to detect unexpected events and to initiate rapid compensatory responses (Dietz 2003). Proprioceptive information also provides the basis for the conscious representation of our body in space during locomotion (Dietz 2003).

In fact locomotion produces multisensory afferent input which is coordinated by the information from CPGs in the brainstem, cerebellum, basal ganglia and cerebral cortex (Dietz 2003).

It is well known that any damage to the tripartite motor control system leads to a movement disorder. For example, cerebral or spinal lesions are associated with the impairment of spinal reflex activity (Zehr and Duysens 2004). This leads to the defective processing of peripheral input by central mechanisms. The result is a loss of inhibition and hyperexcitability of short-latency reflexes while the facilitation of the functionally more important polysynaptic reflexes is reduced. It is not yet known how far the impaired reflex behaviour is mediated by CPGs or, alternatively, how directly it is due to changes in descending signals bypassing the CPGs during locomotion (Forssberg and Dietz 1997).

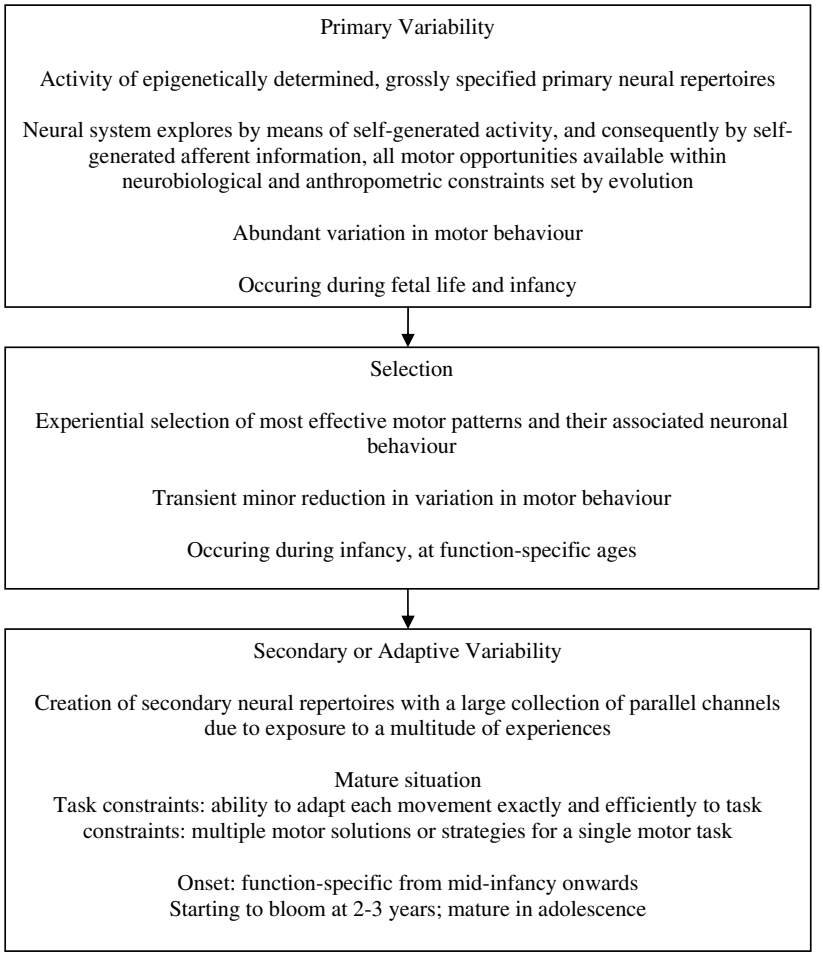
5.2.4 Neuronal Group Selection Theory (NGST) and CP

One of the principal properties of normal development is variation (Touwen 1993). Variation is present in practically all developmental parameters such as motor performance, developmental sequence, or the duration of developmental stages (Touwen 1993). In 1989, Edelman developed a theoretical concept of neural development, the Neuronal Group Selection Theory (NGST). This theory offers a balanced combination of the theories of neuromaturation, such as reflex/hierarchical theory, and the theories of interactive physical systems, such as dynamic systems theories (DST), and facilitates the understanding of the effects of brain damage at an early age (Hadders-Algra, 2000a, b). According to the NGST, the brain or more specifically, the ensemble of cortical and subcortical systems is dynamically organised into variable networks, the structure and function of which are selected by development and behaviour. The units of selection are collections of hundreds to thousands of strongly interconnected neurons, called neuronal groups, which act as functional units. This selection matches the possible motor commands to constraints imposed by neural and body structure (Sporns and Edelman 1993). The NGST highlights the notion that development is the result of the complex inter wining of information from genes and environment. Similar ideas had already been proposed by Gottlieb in 1991. He drew special attention to the role of species-and age-specific behaviour, which could play a directing or canalising role in motor development by exposing the individual and specific experiences. The presence of age-dependent canalising behaviour of this kind had already been noted by McGraw in 1989, he reported that children exhibit an indomitable urge to exercise a function as soon as it emerges (McGraw 1989).

The variation has two forms: primary variability, which is not geared to external conditions, and secondary variability, in which motor performance can be adapted to specific situations (**Figure**

1). In both cases, the selection on the basis of afferent information plays a significant role. Sensory information thus performs an important function in motor development (Hadders-Algra 2000b).

Figure 1. **Motor development according to Edelman's Neuronal Group Selection Theory**



In children with CP the clinical care has focused primarily on spasticity, musculoskeletal malformations, dyskinesia and persistent infantile reactions. The other problems including the syndromes like paresis and dyscoordination have received relatively little attention. This lack of attention is probably related to our poor knowledge of these phenomena (Hadders-Algra 2000b).

The theory shown in figure 1 can perhaps offer a framework to facilitate an understanding of this basic type of dysfunction of children with CP. During the first postnatal months, the poor variation is expressed in a limited repertoire of general movements (Prechtl 1997). When goal-directed motility emerges, reduced variation continues to be the main mark of motor behaviour in these children showing only a little variation in spontaneous posture and motility (Prechtl 1997, Hadders-Algra et al. 1996).

The studies in which the postural abilities of children with CP were assessed with the aid of perturbation experiments revealed that these children possess direction-specific postural

adjustments (Brogren et al. 1996, Woollacott et al. 1998), but the variations revealed that the repertoire of the direction-specific postural adjustments in these children is significantly reduced (Hadders-Algra et al. 1996, Brogren et al. 1998, Roncesvalles et al. 2002). A limited repertoire of the primary neuronal networks is not the only deficit in children with CP, children with CP also have impairments in processing various forms of afferent information (e.g. proprioceptive deficits) (Nashner et al. 1983, Filloux 1996, Roncesvalles et al. 2004), tactile information (Yekutiel et al. 1994, Roncesvalles et al. 2001, Clayton et al. 2003), or visual information (Foster et al. 1996, Cioni et al. 2000). It is conceivable that sensory deficits interfere with the experience-dependent selection of the most effective neuronal networks in the pool of primary networks, impairing sensory-motor integration and the formation of optimal internal representation (Hadders-Algra 2000a,b). Internal representations are abstract models of one's own body and its interaction with the external world. The brain contains multiple representations of the body (Haggard 2005). First, the afferent inputs from the skin and the proprioceptive receptors project to maps of the body surface and body segments respectively in the primary somatosensory cortex. These somatotopic maps reflect the distribution of sensory receptors within the body, and underpin the somatic sensation, body awareness. Neuroanatomical, neuropsychological and neurophysiological evidence all suggest that this primary information is further processed to a more cognitive representation of the body. These representations provide a supramodal, coherent scheme for body representation and optimal motor control and learning (Haggard 2005).

Many children with CP are not able to detect or perceive a tactile stimulus on their affected body part (Roncesvalles et al. 2001, Clayton et al. 2003). This deficit disturbs the formation of the functional body scheme, because the body scheme integrates tactile information from the body surface with proprioceptive information about the configuration of the body in space (Farrer et al. 2003). Another thing that affects the building of an adequate body scheme is the lack of movement-related afferent information from the affected body parts, due to paresis or contractures (Brown et al. 2000).

Recent studies support the idea that deficits in sensory processing contribute to the variation in the scaling of motor output in children with mild to moderate forms of CP (Eliasson et al. 1995, Hadders-Algra 2000a,b). These task-specific studies have shown that practice, implying the repetition of self-generated sensory input (Gordon et al. 1999, Eliasson and Gordon 2000) and the augmentation of movement related afferent tactile and proprioceptive information, results in a reduction in the variation in motor output and thereby in a better task-specific adaptation of motor behaviour (Gordon et al. 1991, Hadders-Algra 2000a, Farrer et al. 2003) (**Table 4**).

Table 4. Neuronal Group Selection Theory and development motor disorders (Hadders-Algra 2000a)

Nervous system	Motor dysfunction	Clinical diagnoses
Deficits in primary variability		
No appropriate functional activity in primary neuronal networks	Very stereotyped motor behaviour with virtually no variation Postural control: absence of direction specificity	Severe CP
Reduced repertoire of primary neuronal networks	Stereotyped motor behaviour with little variation Postural control: presence of direction specificity, reduced number of postural variation	Mild and moderate forms of CP Complex MND
Deficits in selection		
inappropriate processing of afferent information	Prolonged persistence of non-adaptive primary variation in motor behaviour	CP (all forms) Complex MND
Deficits in secondary variability		
Inappropriate coordination of parallel networks of secondary neuronal repertoires	Inappropriate selection of best motor solution for specific motor tasks Non-adaptive variations in motor performance due to non-optimal temporal and quantitative scaling of motor output	CP (all forms) Complex MND Simple MND

5.2.5. Neuroplasticity

The term brain plasticity or neuroplasticity refers to the inherent capacity and resilience of the brain to undergo structural and functional modifications (Drubach et al. 2004). Quantitatively and qualitatively different neuroplastic mechanisms are triggered by various natural or artificial stimuli (like ES). Plasticity may have both positive and negative effects during development (evolutionary plasticity), it may become evident after transient exposition to a biologically significant stimulus (reactive plasticity), it may result from long-term or repeated exposure to such stimuli (adaptation plasticity), or it may participate in the functional recovery of damaged neuronal stimuli (reparation or restorative plasticity) (Trojan and Pokorny 1999).

Plastic changes may occur at three levels: synaptic level, local neuronal circuits and multimodular level. The synaptic level of neuroplastic changes is typical for mechanisms of learning and memory. It can be expressed as a long-term increase (potentiation) or decrease (depression) in the efficacy of synaptic transmission (Martin 2002). In mammals, a cellular mechanism of long-term potentiation was first identified in the hippocampus. It is now known that a similar mechanism exists in the neocortex and contributes the motor skill of learning, for excample (Sanes 2003). Neuroplastic processes at the level of local neuronal circuits may follow changes in the intensity of afferent input. For example, after partial denervation, synapses which have lost their connections degenerate, while the remaining ones with intact input proliferate and form new functionally active contacts in the locations of those lost. This form of plasticity appears to be a manifestation of the ability of the brain to recover after damage (Trojan and Pokorny 1999). Neuroplastic processes at the multimodular level support new relationships between the individual functional regions of the brain (Drubach et al. 2004). Neuroimaging techniques have led to suggestions that brain damage can be accompanied by complex patterns of cerebral reorganisation.

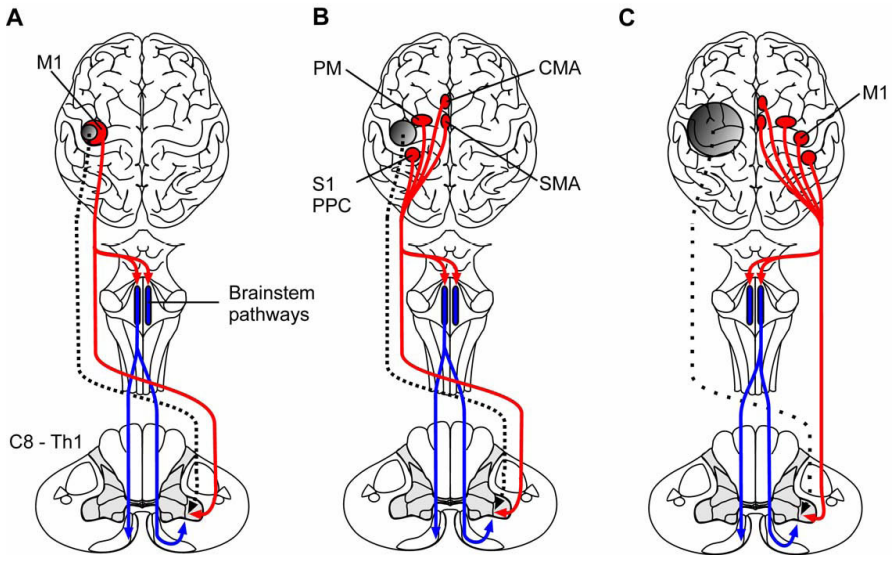
5.2.5.1 Motor reorganisation

Normally the large majority of the corticospinal (CS) projections are indirect and terminate in spinal interneurons and propriospinal neurons; the corticospinal tract also sends a large number of collaterals to subcortical structures such as the reticular formation (brainstem descending pathways) and the basal ganglia (Kuypers 1981). Eighty to ninety percent of the CS axons cross the midline at the medullospinal junction, forming the pyramidal decussation, and run down in the dorsolateral funinculus of the spinal cord. The remaining 10-20 % of uncrossed CS axons descends either in the dorsolateral funinculus or in the anterior funinculus where they form the anterior CS tract. Most of the axons which run in the anterior CS tract decussate in the spinal cord and terminate in the medial motoneurons that control the axial and proximal limb musculature (Davidoff 1990).

Several patterns of CS projections directed at the motoneurons of the paretic hand have been disclosed in children with CP by means of TMS (Farmer et al. 1991, Eyre et al. 2001).

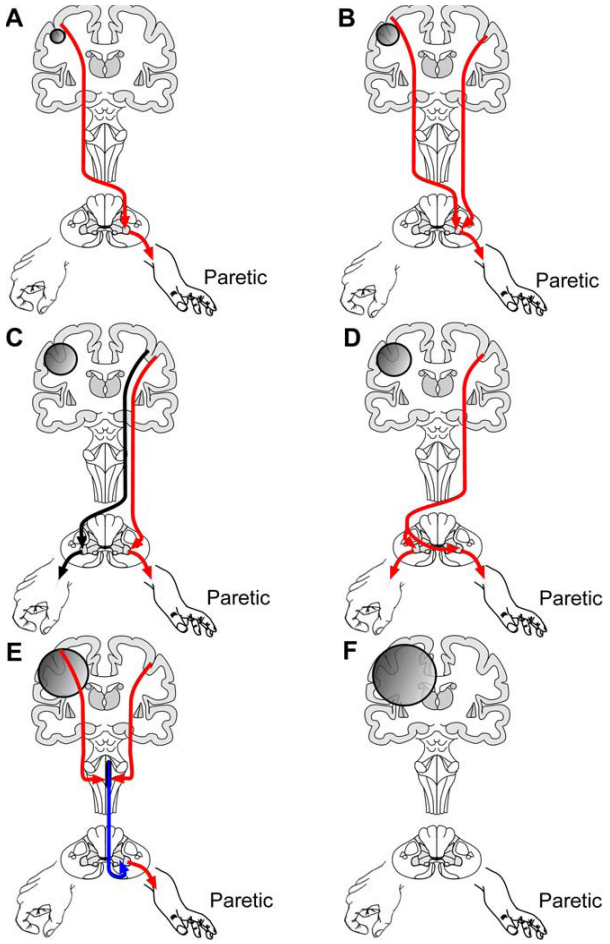
According to Vandermeeren (2002, 2003a,b) after an early brain injury leading to congenital hemiplegia, the motoneurons of the paretic hand muscles may receive a cortical drive through 1) crossed CS projections, 2) both crossed and ipsilateral CS projections, 3) strictly ipsilateral CS projections, 4) CS projections originating from the undamaged hemisphere and bilaterally branched to both sides of the spinal cord, 5) the brainstem descending pathways or they may 6) be devoid of demonstrable descending projections (**Fig. 2 and 3**).

Figure 2. General mechanisms of motor reorganisation (Vandermeeren 2003a)



After an injury to the primary motor cortex (M1) or the corticospinal tract (grey area and black dashed line, respectively), functional recovery may involve the perilesional cortex (A) which sends parallel corticospinal projection (red), the ipsilesional pre- or post-central areas (B) and/or the undamaged hemisphere (C). The brainstem descending pathways (dark blue) might be involved and associated with these three patterns of reorganisation (see text). M1: primary motor cortex, PM: premotor cortex, CMA: cingulate motor areas, SMA, supplementary motor area, S1: primary somatosensory cortex, PPC: posterior parietal cortex. Adapted Vandermeeren, 2003a

Figure 3. Reorganisation patterns of the corticospinal tract in congenital hemiplegia (Vandermeeren 2003a)



Red arrow: corticospinal (CS) axons projecting onto the motoneurons of the paretic hand,
dark arrow: crossed CS axons projecting to the non-paretic hand's motoneurons,
blue arrow: reticulospinal projections.
The grey disk represents the early brain injury resulting in CH. Note its hypothesised growing extent from A to F.

A) "Normal" crossed CS projections from the damaged hemisphere,
B) Motoneurons of the paretic hand innervated by both crossed CS and ipsilateral CS projections (which could be either non-branched or branched as described in C and D),
C) non-branched ipsilateral CS projections distinct from the crossed CS projections devoted to the contralateral non-paretic hand, D) CS projections from the undamaged hemisphere bilaterally branched to the homologous motoneurons pools,
E) involvement of the brainstem descending pathways (mostly the reticulospinal tract),
F) absence of demonstrable descending projections from either hemisphere to the paretic hand's motoneurons.
Adapted from Vandermeeren, 2003a

5.2.5.2 Restorative plasticity in CP

In children with CP the goal of restorative CNS plasticity is to ensure the recovery of voluntary movements by providing the appropriate cortical drive to the spinal motoneurons and interneurons. It is likely that functional compensation involves activity-dependent mechanisms that modify the synaptic strength or the neuronal excitability and/or the synchronisation between neuronal populations, On the other hand, structural reorganisation, such as the reconstruction of a neuronal network, or connections distrupted by synaptogenesis and axonal/dendritic sprouting may also be involved in functional recovery, even when the injury occurs after the end of the developmental period (Nudo 2003, Vandermeeren 2003a,b).

Functional impairment after damage to the nervous system may not always be due to structural damage but instead to diaschisis. The concept of diaschisis describes the phenomenon in which structurally intact brain areas become functionally impaired because of loss of input from

anatomically connected injured areas of the brain (Drubach et al. 2004). In the disconnected areas there is a decrease in neuronal activity and metabolism (Vandermeeren 2002, Butefish et al. 2003). In the case of CP, extensive zones of diaschisis can involve the thalamus, basal ganglia or remote cortical areas according to the lesion pattern, and thereby influence the clinical form of CP (Vandermeeren 2002).

5.3 Gross motor function

5.3.1 Postural control

One of the major goals of human postural control is the maintenance of the vertical posture of head and trunk against the forces of gravity, as the vertical orientation of the proximal parts of the body provides an optimal condition for vision and goal-directed motility (Massion et al. 1998, Hadders-Algra et al. 1998, Forssberg 1999b). This creates a base for adequate reaching, sitting, standing and walking. Studies of the development of postural adjustments in young sitting children reveal that largely direction-specific muscle activation patterns are already present in five to six month old children who are not able to sit without support (Hadders-Algra et al. 1996, 1998). Direction specificity denotes the presence of a specific set of muscles which are activated in concert during a perturbation of the body in a specific direction. This means that, with sitting and standing adults, the muscles on the dorsal side of the body are primarily activated during a sudden forward sway of the body and the muscles on the ventral side are primarily activated during a backward body-sway (Forssberg and Hirschfeld 1994, Hadders-Algra et al. 1998).

The basic, direction-specific muscle activation patterns can be modulated on the basis of multi-sensorial input from visual systems, the vestibular and somatosensory systems, the latter source of information probably being the most important in normal standing conditions (Massion et al. 1998, Hadders-Algra et al. 1998).

Forssberg and Hirschfeld (1994) proposed a CPG model to explain the neural organisation of postural adjustments. The model has two functional levels, which are active prior to response execution. The first level deals with selection of the basic, direction specific muscle activation pattern, while the second level controls the fine-tuning of the selected pattern to task-specific, multi-sensorial afferent information.

According to Hadders-Algra et al. (1998) it was concluded that postural control during sitting is organised in basic, direction specific synergies which can be adapted to task-related conditions. The flexibility in the flexor synergy elicited during forward sway is larger than the flexibility in the extensor synergy evoked during backward sway. A “fixed” extensor synergy is predominantly present between nine months and three years of age, i.e. during the period when standing and walking abilities develope. With increasing age the “fixed” extensor synergy gradually dissolves.

At toddler age, all the direction-specific leg, trunk and neck muscles are activated in conjunction with a large amount of antagonistic co-activation (Hadders-Algra et al. 1996, Forssberg 1999a,b). This “muscular corset strategy” may be a smart solution to mastering the large degrees of freedom present when a child starts to move in the upright position (Forssberg 1999b). The interaction between different sensory (somatosensory, visual and vestibular) systems develops, resulting in a dynamic adaptation of the response pattern that is dependent on external conditions.

The development of postural adjustments in sitting position during the first half year of life was studied by Hedberg et al. (2005) and they indicated that postural development starts with an innate repertoire of direction-specific postural adjustments, which include the adjustments of all direction specific muscles. With increasing age, they initially almost disappear and then return after the age of three months. The finding that postural activity is first clearly associated with

spontaneously occurring motor behaviour after the transition at three months suggests that, around the age of three months a significant change occurs in the circuitries controlling the posture.

Hedberg et al. (2004) studied the early development of postural adjustments in standing with and without support. The early ontogeny of postural adjustments during standing follows the same principles as that of postural adjustments during sitting. It starts with variable direction-specific and task-dependent postural adjustments present before independent standing. Development differs to some extent for ventral and dorsal muscles. Initial phases are characterised by a preference for the top-down recruitment of the postural muscles (Hadders-Algra 2005, Hedberg et al. 2004).

5.3.2 The influence of sensory stimulation on motor development

Research suggests that the ability to relate sensory input to motor output forms the basis of posture control development. As the infant learns to sit and stand the rules linking the sensory and motor systems are extended to the trunk and legs (Woollacott et al. 1987, Hadders-Algra 2005). The single sensory control of posture emerges first in young infants, with vision being the dominant sense in pre-sitting and newly sitting infants. As the infant gains experience of sitting, reliance on vision decreases and postural responses appear to be initiated through somatosensory input, with vision playing a modulatory role. A reliance on vision is again seen during transitions, such as to independent walking, but the ability to mediate correct motor responses in sensory conflict situations does not emerge until late (Cioni et al. 1996, 2000).

5.3.3 The development of muscle-tone dysregulation

In spastic CP, evidence of abnormal segmental and supraspinal control of motor neuron output exists. Impaired Ia inhibition of antagonist muscles and decreased nonreciprocal Ib inhibition have been suggested. Furthermore, early cerebral injury results in reorganisation of supraspinal (corticospinal) inputs to motor neuron pools. Animal models and certain specific human diseases provide examples of the way this circuitry may be disturbed (Forssberg and Dietz 1997, Filloux 1996, Forsberg 1999a, Dietz 2002).

In general, the term spasticity refers to an abnormality of muscle tone in which there exists a "velocity-dependent increase in tonic stretch reflexes" generally associated with increased resistance to passive stretch reflexes (hyperreflexia and clonus), abnormal plantar responses (Babinski reflexes) and the impairment of voluntary movements (Young 1996).

Effective motor movement can be simply viewed as the concerted activation of synergistic alpha motor neurons, often accompanied by the inhibition of motor neuron pools innervating opposing (antagonist) muscle groups. Local (segmental) input to these alpha motor neuron pools comes via Ia afferent fibres from muscle spindles that produce monosynaptic excitatory synapses on homonymous alpha motor neurons (Young 1996, Filloux 1996). Ia afferent fibres also synapse on segmental inhibitory interneurons (Ia inhibitory neurons), which in turn inhibit alpha motor neurons innervating antagonist muscles. This latter inhibitory (polysynaptic) pathway is known as I a reciprocal inhibition. The other inhibitory pathway is called nonreciprocal inhibition in which Ib afferents from Golgi tendon organs make polysynaptic connections with alpha motor neuron pools, producing the inhibition of homonymous alpha motor neurons via the Ib inhibitory interneuron (Young 1996, Filloux 1996) **Figure 4.**

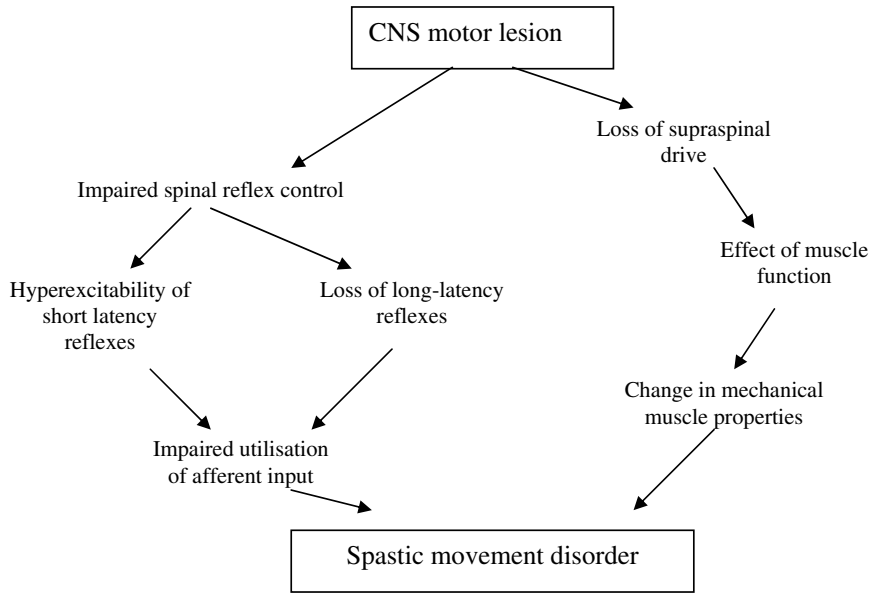
Experimental evidence supports the conclusion relating to the pathophysiological mechanisms of spasticity (Filloux 1996):

1. Reduced reciprocal inhibition of antagonist motor neuron pools by Ia afferents
2. Reduced presynaptic inhibition of Ia afferents
3. Reduced nonreciprocal inhibition by Ib terminals.

In healthy humans, tendon vibration produces the inhibition of H-reflex responses (the latter representing an indirect measure of alpha motor neuron excitability). The reduced presynaptic inhibition of Ia afferents has been deduced in CP by studying the inhibition of H-reflex responses by tendon vibration (Brouwer et al. 1998). Nonreciprocal Ib inhibition has recently been found to be impaired and even supplanted by facilitation in spastic patients with sustained hypertonia.

One of the disturbed processes in spastic CP involves the failure of the reciprocal inhibition of antagonist muscle groups during the contraction of agonist muscles (Filloux 1996). In fact, this co-activation of agonist/antagonist muscle groups may be particularly characteristic of CP. Brouwer and Ashby (1992) demonstrated this using transcranial magnetic stimulation on subjects with spastic quadriplegia while recording either surface EMG responses or single motor units. In healthy subjects, cortical stimulation produces the differential activation of tibialis anterior versus soleus motor neurons. The powerful facilitation of the former occurs with little or no activation of the latter. Interestingly, in subjects with spastic quadriplegia, similar magnetic stimulation results in the virtually equal facilitation of both motor neuron pools, manifested by the comparably short latency activation of both the tibialis anterior and the soleus muscles.

Figure 4. Schematic diagram of the mechanisms that contribute to spastic paresis and spastic movement disorder. A central motor lesion leads to an impaired reflex control by the CPG and to a loss of long-latency reflexes, as well as changes in muscle properties. The consequence is a hyperexcitability of short-latency reflexes, as well as changes in muscle properties. The combination of all the sequelae of the primary lesion leads to spastic movement disorder. CNS, central nervous system; CPG, central pattern generator (adapted from Dietz 2002).



5.3.4 Muscle composition, disuse and contracture

5.3.4.1 Muscle composition

The normal control of movement requires the activation of the skeletal muscles, the lower motor neurons, the spinal region connections, the descending tracts, the control circuits and the motor planning areas (Forssberg and Dietz 1997, Forssberg 1999a, Dietz 2002)**.**

The motor system consists of two integrating parts: central and peripheral. The central motor system has components throughout the central nervous system, including the cerebral cortex, basal ganglia, cerebellum, brain stem and spinal cord. The peripheral motor system includes muscles and both motor and sensory nerve fibres (Wise et al. 2001).

Muscles are complex structures which consist of contractile tissue and connective tissues (Farmer and James 2001). Whole skeletal muscles are composed of numerous bundles or fascicles of muscle fibres. Muscle fibres are composed of myofibrils arranged in parallel. Myofibrils are composed of sarcomeres arranged in series. Sarcomeres contain inter-digitating contractile actin and myosin filaments (Kandel et al. 1995).

Each muscle fibre is innervated by only one motor neuron, but each motor neuron innervates a number of muscle fibres. All muscle fibres innervated by a given motor neuron contract in response to an action potential in the motor axon and the motor neuron and all the muscle fibres it innervates therefore represents the smallest functional unit controlled by the motor system, the motor unit (Kandel et al. 1995). All muscle fibres belong to a motor unit and have similar physiological and biochemical properties. Motor units can be classified according to these properties (Kandel et al. 2002).

The first type is called fast fatigable, the fibres contract and relax rapidly but fatigue rapidly when stimulated repeatedly. The second type is called slow fatigue-resistant. These fibres have much longer contraction time and are highly resistant to fatigue. The third type is termed fast fatigue-resistant. The physiological properties of the fibres are intermediate between those of the other two.

All three types of motor units are found in most muscles but in different proportions. The slow motor units are the most heavily used, because they are recruited in all contractions. The fast motor units are only recruited when greater forces are required and this explains why they are less frequently used (Kandel et al. 2002). When an action potential in a motor axon reaches the muscle fibre contraction is triggered by the depolarization of the muscle fibre.

The sliding filament theory proposes that a muscle contraction arises from cyclical interactions between actin and myosin filaments. During a contraction, the globular heads of the myosin molecules attach themselves to receptor sites on the actin molecule, forming cross-bridges between the actin and myosin filaments. The cross-bridges have spring-like properties and are active elastic elements of the sarcomere contributing active stiffness which is represented by spring constant (change in muscle force corresponding to a unit change in length) (Kandel et al. 2002). Muscle also has a number of non-contractile cytoskeletal components. One of them is titin and it determines the passive elastic properties of the muscle fibre and contributes to the passive resistance or stiffness (DeDeyne 2001). This constitutes the relationship between passive resistive torque and joint displacement (Bressel and McNair 2002). Collagen and the elastic fibres of connective tissues and tendon of the muscle also have elastic properties.

Another component of passive stiffness is a viscous element which provides resistance to stretch. This resistance increases with the speed of stretch (Kandel et al. 2002). It is largely dependent on the thixotrophy phenomenon. Thixotrophy has been defined as the physical change in a substance after it is mechanically agitated. In practice, this means that the gel substances become less viscous (i.e. more fluid) with movement and gradually regain their gelatinous state with rest. In the muscle, thixotrophic changes occur in the gel component of muscle (e.g. proteoglycans and

water) and the viscous resting myosin actin cross-bridges (Whitehead et al. 2001, Bressel and McNair 2002). Molecular bonds of substance are involved in this phenomen, as the bonds are disrupted by movement and reformed when the movement forces cease. Thixotrophy is also dependent on movement history so that previous movement reduces stiffness, whereas previous stillness increases stiffness (Whitehead et al. 2001).

5.3.4.2 Disuse atrophy

Prolonged periods of muscle disuse due to immobilisation or physical inactivity, for example, can result in a significant loss of muscle mass and strength, disuse atrophy. Because it is difficult, if not impossible to investigate, the mechanisms responsible for disuse muscle atrophy in humans, animal models have been developed to mimic human disuse atrophy. Using the rat hind-limb suspension and limb immobilisation models, it has been demonstrated that disuse muscle atrophy occurs due to both a decrease in muscle protein synthesis and an increase in the rate of proteolysis. Lack of exercise and mechanical stimuli during disuse results in the diminished activity of insulin-like growth factor I. Reduced insulin-like growth factor signalling leads to the diminution of muscle protein synthesis (McKoy et al. 1999). At the same time, several proteolytic systems contributing to the degradation of muscle proteins are activated (Powers et al. 2004).

There is also evidence that the number of mitochondria and capillaries are reduced due to the diminished use of the muscle. After three days of unloading the structure of titin has been shown to change reducing its elasticity in the rat soleus muscle. The lack of elasticity in atrophied muscle fibres may cause a decrease contractile function (Goto et al. 2003). Recently, Jones et al. (2004) provided a comprehensive profiling of genes recently associated with atrophy and anabolism during immobilisation and subsequent rehabilitation in human.

5.3.4.3 The development of contractures

The primary symptoms of children with CP, muscle weakness, co-contraction, spasticity and spasms often lead to secondary disabilities such as contracture. These features have been related to CP so that high resistance to passive stretch, hypo-extensibility and intrinsic muscle shortening prevent full range of motion (Cadenhead et al. 2002). More specifically, contractures can be divided into Group I and Group II types. The first type, often called myotendinous contracture, is regarded as a normal process of muscle length adaptation in response to abnormal muscle activation. It occurs in muscles which are continuously kept in a shortened position, usually because of over-activity in the antagonist muscles. As in other conditions the short muscle fibres lose sarcomeres, but, in chronic situations the connective tissue of the muscle also decreases in length and elasticity (Farmer and James 2001).

If the short muscle cannot be used, it undergoes disuse atrophy (Shad et al. 2001). The study of rats by Goldspink et al. revealed that, following immobilisation in a shortened position, the muscles underwent atrophy showing a net loss of muscle protein (Goldspink et al. 1974). When the shortened muscles are not treated adequately, there is a danger that contracture will develop. It not only causes the tightness of muscles and connective tissue but also alters the thixotrophic properties of the muscle. In the state of contracture, passive stiffness is increased and even minor changes in joint angle cause substantial resistance to the movement. During immobilisation, the gel component of muscle becomes more viscous and produces increased resistance to stretching. This viscous resistance of a muscle decreases after exercise (Meyer and Wideman 1997). It is not known whether resting myosin-actin cross-bridges contribute to increased viscous resistance in muscles other than spastic ones.

Contracture also affects the properties of dorsal horn neurons which undergo plastic changes in stiffness. The results of experimental contracture in rats reveal that neurons which before

contracture only reacted to normal motion signals changed their behaviour and responded as mechanical stimuli; in other words, they were nociceptive (Ushida and Willis 2001).

6. THERAPY AND REHABILITATION OF CEREBRAL PALSY

6.1 Conventional therapies

6.1.1 Early intervention therapy

"Early intervention" is a term that encompasses a range of stimulation and training activities for a variety of infants and young children. The particular type of programme that is provided has often been a function of the perceived needs of the children who are being served and the philosophical orientation of the discipline involved (Simeonsson et al. 1982).

The majority of the published studies relate to therapies designed to prevent or minimise CP symptoms in preterm (and full-term) infants. Hur (1995) published a review article about all the studies of therapies for CP that had been found in the English medical literature from 1966 to 1994. He found 37 studies in all, seven of which were controlled and the rest more descriptive or consisting of single-case articles or surveys. Two of the controlled studies revealed a significant difference between two groups after different types of therapy. The positive outcome in both studies was an improvement in motor and social skills and easier home management in altogether 34 children with CP, aged between five months and five years (Hur 1995).

6.1.2 Family-centred functional therapy

The principles of this approach include an emphasis on functional performance constraints and providing therapy when movement patterns are amenable to change. The therapy focuses on identifying and changing performance constraints in the task, the child or the environment.

The following clinical principles by Law et al. (1998) define this approach.

1. Promote functional performance: Functional (activity and context) should direct behaviour. The goal in therapy is to enable a child to accomplish an identified task, rather than promote change in an impairment or development sequence, or change the way in which a task is accomplished to make it more "normal".

2. Identify periods of change: The optimal time to intervene is when a child is trying to perform a new task or perform a task in a different way. The child must be motivated to accomplish a task. A young child's parents are the best people to identify when a child is trying to perform a task.

3. Identify and change the primary constraints in the task, child and/or environment that prevent achievement of the task: Parts of tasks or the environment can be changed (e.g. different toy sizes; less noise). Change in a child's abilities (e.g. strength) can also be targeted during intervention. Tasks incorporated in the daily routine of the child provide an increased opportunity to find solutions to functional motor challenges.

4. Encourage practice: Young children must practise a newly found motor skill. Practising activities is the rule for children without disabilities developing any new skill. Tasks should be practised in a variety of environments which facilitate the completion of the task and promote the flexible use of movement strategies (Law et al. 1998, Law 2003).

6.1.3 Sensorimotor approaches

The term "sensorimotor" is used widely to refer to many kinds of approach to intervention that link sensory input to motor performance. Piaget described a sensorimotor period of development that encompassed the first two years of life. Most sensorimotor intervention approaches are based on Piaget's assumption that children learn about their bodies and their environments through

sensorimotor exploration (Miller and Kinnealey 1993). Children learn about their bodies through the sensory feedback generated by movements (Bundy et al. 2002). They develop an expanding repertoire of increasingly complex actions that enable them to learn about causality, space and objects. This inter-relationship between sensory input generated through active engagement with the environment and the development of skills and knowledge is the foundation of all sensorimotor approaches. Children learn through doing (Bundy et al. 2002). The differences between sensorimotor approaches (SA) from sensory integration (SI) are the following: typically SA are often performed with a group of children rather than individually, like SI, and SA are highly structured compared with SI, which is flexibility and spontaneity characteristic of intervention based on SI theory relating to client-directed activities tailored to individual needs (Bundy et al. 2002).

Bumin and Kayihan (2001) investigated the effects of individual and group approaches to sensory-perceptual-motor training in children with CP. Forty-one children were randomly divided into three groups, 16 children in each training groups (one group received individual therapy and the other group therapy) and nine children in a control group (only a home programme was given). The SPM training programmes were applied for 1.5 hours, three days week for three months. The results indicated that both group and individual treatments had a measurable effect that was consistently greater than that of controls. It was concluded that SPM training in children with CP will be recommended for combined programmes and the relationship with individual and group treatments will be developed.

6.1.4 Physiotherapy

6.1.4.1 Theories behind physical therapy (PT)

The theory behind physical therapy practice is continually changing, based on current knowledge of the central nervous system (CNS). Theoretical models used to explain or justify PT for patients with neurological impairments are based on assumptions relating to how the CNS operates and responds. Many classic neurophysiological treatment approaches have been based on facilitation (Gordon 1987, Bobath 1967). According to Ostrosky (1990) in Gordon's review, there are five basic assumptions in the facilitation model. The first assumption, based on the work of Jackson, is that the brain controls movements, not muscles. The assumption of the second model is based on Sherrington's stimulus-response concept of behaviour. The idea is that a patient's movement patterns can be altered by applying specific patterns of sensory stimulation, especially through proprioceptive afferent pathways. The third assumption is that the CNS is hierarchically organised: higher centres control lower centres and lower centres control primitive and more automatic behaviours. Abnormal movement patterns and tone disorders are assumed to result from a lack of inhibitory control by the higher centres. The fourth assumption is that recovery from brain damage follows a predictable sequence that parallels the development of normal motor behaviour from infancy. This idea is based partly on the third assumption, in the developmental sequence the higher centres are said slowly to gain control over the more primitive lower centres. The last assumption is that all motor phenomena associated with brain damage have a neurophysiological basis (Gordon 1987, Ostrosky 1990).

Bobath (1967) suggested that normal voluntary movement is based on a combination of reflexes, some elicited by peripheral stimuli and others elicited by stimuli resulting from movement. The Bobath concept emphasises observation and analysis of the clients' current functional skill performance (Mayston 2002). As the Bobath concept initially followed a developmental approach, it soon became known as "neurodevelopmental therapy" (NDT). It has evolved independently in

different countries and some slight differences of interpretation have occurred (Bobath and Bobath 1984).

NDT exercise programmes include the facilitation of movement technique and automatic postural responses and the control of the influence of abnormal movement patterns.

PT and rehabilitation in children with CP is aimed at the prevention of abnormal muscle tone (Bobath and Bobath 1984, Mayston 1992, Mayston 1996), improving postural alignment by specific handling techniques and then working for better active participation and practice of specific, relevant, functional skills (Mayston 1992). Facilitation provides a very useful initial technique for use with the young infant and parents soon learn the key points in handling and controlling movement, the most appropriate positions for daily activities and the best movement patterns to assist the development of their child. The techniques of facilitation can be used in association with other techniques in ongoing treatment programmes (Bobath and Bobath, 1984, Hylton 2000).

Ottenbacher and co-workers (1986) conducted a meta-analysis of studies which investigated the effects of NDT in paediatric populations. Their reports showed that clients receiving NDT or a combination of NDT and other interventions performed better than 60% of participants receiving other treatment modalities (Ottenbacher et al. 1986).

The American Academy for Cerebral Palsy and Developmental Medicine recently published a review of the evidence relating to NDT as a treatment approach for children with CP. This extensive report concluded that there is no strong evidence supporting the effectiveness of NDT for children with CP when it comes to normalising their muscle tone, increasing their rate of attaining motor skills and improving their functional motor skills (Butler and Darrah 2001).

6.1.5 Sensory integration therapy (SI)

Sensory stimulation is a treatment technique that involves the application of direct sensory stimulation with the aim of eliciting a generalised behavioural response, such as increased attention or calming (Ayres 1972, Bundy et al. 2002). Sensory stimulation is always provided most effectively in the context of active engagement in meaningful activity. SI and sensory stimulation are not synonymous (Bundy et al. 2002).

Sensory integration theory has a long history. Originally, Ayres, an occupational therapist with advanced training in neuroscience and educational psychology, developed the SI theory to explain the relationship between deficits in interpreting sensation from the body and the environment and difficulties with academic or motor learning (Ayres 1972, Bundy et al. 2002).

SI theory has three components. The first pertains to development and describes typical sensory integrative functioning; the second defines sensory integrative dysfunction; and the third guides intervention programmes. Each component in turn has a major, overarching postulate. The three major postulates of SI theory are:

1. Learning is dependent on the ability to take in and process sensation from movement and the environment and use it to plan and organise behaviour
2. Individuals who have a reduced ability to process sensation may also have difficulty producing appropriate actions, which in turn may interfere with learning and behaviour
3. Enhanced sensation, as a part of meaningful activity that yields an adaptive interaction, improves the ability to process sensation, thereby enhancing learning and behaviour (Bundy et al. 2002)

The sensory integration and praxis test (SIPT) is a battery of 17 tests designed to evaluate several aspects of praxis, as well as some aspects of somatosensory and visual discrimination and postural control in children aged between four and eight with mild to moderate learning or motor difficulties. Their primary use is to contribute to an understanding of a child's difficulties and

planning (Ayers 1989). This is a standardised test based on a nationwide sample of approximately 2000 children.

For the sample of 10 children with CP (mean age=6.1 years; SD =1.4 years), the scores on all tests in which a motor component was likely were depressed. The group as a whole had trouble on tests involving somatopraxis, visual perception, visual-motor coordination and constructional abilities. They had poor tactile perception. All these problems may be associated with brain damage. The possibility that some of the scores were lowered by the neuromotor deficits was supported by relative strengths in form and space perception tasks that do not involve motor execution (Bundy et al. 2002).

6.1.6 Pharmacotherapy

6.1.6.1 Oral pharmaceutics

Medical treatment is recommended for the treatment of spasticity when it produces a clinical disability, i.e. it interferes with posture, motor capacity, nursing or daily living activities among children with CP. The general goal of medical treatment is to reduce spinal reflex excitability by reducing the release of excitatory neurotransmitters or by potentiating the activity of inhibitory circuits.

A pharmacological approach relies on the use of drugs which modulate neurotransmitters acting at the cortico-spinal level (GABA, glycine, glutamine, noradrenaline, serotonin). The aim of this treatment is to reduce spinal reflex excitability by reducing the release of excitatory neurotransmitters, or by potentiating the activity of inhibitory inputs.

Diazepam increases presynaptic inhibition by stimulating GABAa receptors in the brainstem and spinal cord (Abbruzzese 2002). There are very few studies of medical treatments for spastic CP. In some double-blind studies of patients with spinal cord lesions, antispastic efficacy has been shown. Baclon stimulates GABAb receptors inducing the suppression of excitatory neurotransmitter release. Tizanidine is an $alpha_2$ agonist which binds at both the spinal and supraspinal levels and reduces the presynaptic activity of excitatory interneurons. Benzodiazepines significantly lowered spasticity in a double-blind study of children with cerebral palsy, but the drug doses in cases of severe spasticity with athetosis resulted in unacceptable sedation (Abbruzzese 2002).

6.1.6.2 Oral baclofen

Baclofen's mechanism of action is based on the premise that spasticity is associated with the inadequate release of the inhibitory neurotransmitter gamma-aminobutyric acid (Albright 1996). In a double-blind, cross-over trial of children aged two to 16 with successive four-week treatment periods, baclofen (up to 60 mg/day) was significantly more effective than placebo in reducing spasticity and allowing active and passive limb movement (Pranxatelli 1996). A recommendation was made that the starting dose in children younger than eight years should be 5- 10 mg/day in three divided doses. Because of its poor lipid solubility and relatively high serum concentrations, large oral doses are required to produce effective drug concentrations in the cerebrospinal fluid (CSF). The levels in the CSF are limited by the side-effects relating to these large doses, principally gastrointestinal disturbances and drowsiness (Rang and Dale 1991)

6.1.6.3 Intrathecal baclofen

Continuous intrathecal baclofen (CITB) infusion has been used for severe spasticity in children with CP, but it has also been explored as a potential treatment for dystonic movements which can significantly impair function, be painful and be difficult to treat otherwise (Butler and Campbell 2000, Fitzgerald et al. 2004). CITB has been administered into the lumbar-spinal fluid in bolus injections, via an external pump that delivers a continuous infusion of baclofen, or via a

surgically implanted pump that delivers a continuous infusion (Albright 1996). Oral baclofen results in virtually undetectable levels of the drug in the spinal cord, whereas intrathecally administered baclofen at 1/100th the dose results in cerebrospinal fluid levels comparable to serum levels following oral medication (Penn and Bucci 1987, Albright 1992).

In the review article by Butler and Campbell (2000), seventeen relevant publications were identified. The participants (449) in these studies were diagnosed with spastic type CP or primarily spasticity mixed with the types of abnormal movement or with the dystonic type of CP. The age range was from three to 55 years. The conclusion drawn from this limited evidence was that ITB reduced spasticity in the lower extremities, but the effect is unclear in the upper extremities. Function and ease of care improved. The effects on dystonic symptoms were also generally positive. Medical complications were common but manageable. In the long-term (seven years) safety and efficacy study of CITB, Campbell et al. (2002) concluded that children with GMFCS level IV and V disability benefit substantially in terms of pain and spasm relief, improved sleep, independence and easier care. In the multicentre trial by Gilmartin et al. (2000) 51 candidates were randomised to two groups of intrathecal injections of baclofen or placebo. According to their experience, the ideal candidate for chronic ITB was a patient with CP with moderate to severe spasticity. The treatment is relatively safe, minimally invasive and reversible.

6.1.6.4 Botulinum toxin

The clinical use of botulinum toxin began in 1978 with the treatment of strabismus (Jancovic 1997). Seven immunologically divergent serotypes of botulinum toxin have been recognised and labelled A to G. Of these, the most potent, botulinum toxin type A (BTX-A), is the serotype available for clinical use. The toxins are synthesised as single-chain polypeptides with a molecular mass of about 150kDa, consisting of a heavy chain (about 100kDa) tethered by a disulphide bond to alight chain (about 50kDa) (Brin 1997). They bind with high affinity and specificity to receptors on the cell surface of the presynaptic membranes of cholinergic motor neurons (Brin 1997). Chemodenervation results in a reversible, partially flaccid paralysis, usually lasting 12 to 16 weeks. The recovery of the neuromuscular junction occurs by means of compensatory proximal axonal sprouting and takes place over six to eight weeks in the experimental animal. Functional recovery is well documented in the clinic, where repeated injections are usually necessary to maintain therapeutic benefit (Jancovic 1997, Aoki and Guyer 2001, Jefferson 2004).

In the systematic review by Boyd and Hays (2001), 10 randomised trials evaluating the use of BTX-A in the lower limb in children with cerebral palsy were evaluated. Their meta-analysis of three trials, involving BTX-A and placebo using the physician's ratings scale revealed that the pooled risk difference was 0.25 (95% CI 0.13, 0.37). The corresponding figures for two trials representing the same design but comparing BTX-A, and casting was 0.23 (95% CI -0.06, 0.53). This means that 25% more of the BTX-A treated groups would improve by two or more points on the physicians rating scale compared to the placebo group. The corresponding figure for the trials using BTX-A vs casting was 23 %. They concluded that botulinum toxin type A has a high level and quality of evidence for several treatment goals but a moderate dose-dependent effect on gait.

6.1.7 Surgical and neurosurgical therapy

6.1.7.1 Orthopaedic surgery

The most common reasons for the failure of spasticity management in children are fixed contractures. Orthopaedic surgery focuses primarily on the spasticity and its consequences and consists of soft tissue (muscle and tendon) intervention, neurectomies and bony operations (Miller 2005). In the population-based series by Åhlander (1998), 297 orthopaedic lower limb operations in children with CP aged 16 years were recorded in Sweden. The clinical subtypes consisted of 123 spastic diplegias, 109 spastic hemiplegias, 12 spastic tetraplegias, 40 dyskinetic syndromes and 13

congenital ataxias. In all, 59% of the children underwent at least one orthopaedic operation on the lower limbs during their growth period. This means that approximately one in every thousand of the paediatric population in the studied area required orthopaedic intervention (Åhlander 1998). The most common intervention in this series was gastrocnemius release (34%), followed by adductor myotomy (25 %) and Achilles tendon lengthening (18%). In all, 43 % of the children were four to six years of age at their first orthopaedic intervention and 66 % were operated on before the age of seven. Most of the surgery in Åhlander's series was "soft tissue" surgery (94%) (Åhlander 1998).

In spastic diplegia, the finding that the medial hamstrings are tighter than the lateral ones and that, within the medial hamstring group, the semitendinosus has the most profound contracture is almost universal (Boyd and Graham 1997). Lengthening the semitendinosus with spasticity management to the remaining medial hamstring is therefore a valid option for many children. The distinctive contribution of the gastrocnemius to equinus gait in spastic diplegia has been recognised by many authors (Delp et al. 1996, Borton et al. 2001). The soleus muscle is rarely affected by contracture in spastic diplegia (Graham 2001). A selective lengthening of the gastrocnemius by a Strayer type lengthening may be appropriate (Bleck 1987, Miller 2005).

In hemiplegic lower limbs equinovarus is a very common pattern. Usually the reason for this is combined spasticity/contracture in the gastro-soleus and the tibialis posterior. Persistent varus posture may require surgical correction, by the split transfer of the tibialis posterior (Greene et al. 1991). Studies using gait analysis have also shown that, when lengthening of the Achilles tendon is routinely used with a split tibialis posterior transfer, there can be a high incidence of calcaneus gait and over-lengthening of the calf (O'Bryne et al. 1997).

The optimum age for surgery in the hemiplegic upper limb is usually considered to be between eight and 12 years. In the hemiplegic forearm, the pronator teres is almost invariably the first muscle to progress to fixed contracture (Boyd et al. 2001).

In a prospective study by Graham et al. (2001), self-selected walking speed and the energy cost of walking were measured in a large group of children with CP in every three months after single-event multilevel surgery. After surgery, there was increased dependence on assistive devices and walking speed declined dramatically, while the energy cost of walking increased. (Graham 2001).

One of the most common reasons for the failure of muscle-tendon surgery is the persistence of spasticity. Muscle-tendon lengthening reduces spasticity, but the effects are usually quite short lived. If the underlying spasticity is severe and uncontrolled, recurrent deformities are likely (Miller et al. 1997, Graham 2001). Orthopaedic surgeons who are experienced in both spasticity and contracture management are increasingly using combined interventions. These include the insertion of an inrathecal baclofen pump or injections of BTX-A at the time of muscle-tendon surgery (Molenaers et al. 2004, Graham 2001).

Children who are non-ambulatory and have severe spasticity are more likely to have dislocated hips than those who have mild spasticity and walk independently (Scrutton et al. 1997). However, the surgical correction of dislocated hips is indicated to prevent or manage pain, not to promote walking in a child (Graham 2001).

6.1.7.2 Selective posterior rhizotomy (SPR)

Selective posterior rhizotomy is a neurosurgical method for reducing spasticity, primarily in the lower limbs of children with CP (Abbott et al. 1989, Abbott 1996, Peacock and Staudt 1990). The use of SPR in the treatment of spasticity arose from their success in treating unremitting limb pain. In 1888, an American neurologist, Dana, first suggested cutting nerves to treat pain and his colleaque Abbe adopted the idea. As his experience of the technique grew, he had occasion to operate on patients with painful spasticity (Foerster 1913). In his paper from 1913 Foerster singled out 88 cases with spastic congenital paraplegia from a total 159 patients who he had been subgrouped particularly favourably for posterior rhizotomy because their motor nerves were spared.

However, the density of his lesioning led to unacceptable side-effects, mainly sensory abnormalities and skin sores (Foerster 1913). In 1967, Gros et al. returned to Foerster's posterior rhizotomy operation. They utilised the anatomical fact that each posterior root divides into a number of rootlets. By leaving 20% of the posterior rootlets intact, they were able to prevent sensory loss (Gros et al. 1967).

Fasano et al. (1978) described the use of electromyography (EMG) during electrical stimulation of the posterior nerve rootlets in spastic patients as the basis for selective rootlet division (Fasano et al. 1978). This neurophysiological monitoring allowed Fasano and his co-workers to divide the posterior rootlets into those with a normal response and those with an abnormal response with EMG. The posterior rootlets associated with a normal response were left intact. In their method, the posterior roots are selected and cut at the level of L1 near the conus. This procedure was found to relieve spasticity without significant recurrences or sensory disturbances. It was found to be most useful in spastic cerebral palsy and improvements in function frequently accompanied reductions in spasticity (Fasano et al. 1988, Albright 1992).

A modification, in which the procedure is performed through a laminotomy in the L2-L5 area, was introduced by Peacock and Arens (1982). By working at the level of the cauda equina rather than the conus, the lower sacral nerve roots that supply the bladder and bowel sphincters could be positively identified and spared. In this method the roots are identified by finding their exits in the vertebral interspace. Posterior nerve rootlets were electrically stimulated and selectively divided, based on the EMG and visually observed muscular response (Peacock and Arens 1982, Peacock et al. 1988).

Thirty to fifty per cent of the rootlets at each level were transacted. The resected midline bone, which includes the spinous processes and ligaments, was replaced in its original bed in the hope of preventing future spinal deformity (Aiona and Sussman 2004). Inpatient PT was performed for up to one month after the initial recovery period. Outpatient PT was then performed three to four times a week for up to a year to maximise the benefit of spasticity reduction (Aiona and Sussman 2004).

The vast majority of follow-up studies revealed a significant reduction in spasticity and an improvement in function, not only in terms of sitting and walking but also in terms of hand function and self-care.

In 1998, McLaughlin et al. investigated the efficacy and safety of SPR in children with spastic diplegia, where 43 children were randomly assigned on an intention-to-treat basis to receive SPR plus PT or PT alone. Primary outcome measures were collected at baseline six, 12 and 24 months. Their primary hypothesis was that SDR plus intensive PT would result in a robust decrease in spasticity and a clinically important increase in functional mobility compared with intensive PT alone. The seventeen-patient group was scheduled to receive PT in the following 12-month sequence:

(1) two hours a day, five days a week for four weeks (40 hours)
(2) one hour a day, four to five days a week for the next five months (max 105 hours)
(3) one hour a day, one to four days a week for the next six months

At 24 months, the SPR +PT group exceeded the PT only group in terms of a mean reduction in spasticity. The SPR+ PT group and the PT only group demonstrated similar improvements in independent mobility on the Gross Motor Function Measure (GMFM) (McLaughlin et al. 1998).

The three randomised, controlled studies by Wright et al. (1998), McLaughlin et al. (1998) and Steinbok et al. (1997a) showed a significant reduction in spasticity and an increase in ROM in the children undergoing surgery.

The study by Steinbok et al. (1997a) was a randomised, controlled, single-blind trial to compare selective dorsal rhizotomy plus physiotherapy (SPR + PT group) with physiotherapy alone (PT group) in children with spastic diplegic CP. Fifteen children were randomly assigned to each treatment modality. Both groups had intensive PT for nine months. The amount of PT over the

study period was an average of 81.8 hours (range 72 to 90 hours) for the SPR group compared with 81.3 hours (range 70 to 89 hours) for the PT group during the first three months three times a week and during the remaining six months twice a week. The schedule was the same for both groups and equivalent techniques of treatment were used. The result of the study showed a statistically significant difference in improvement in motor function in favour of the SPR group (GMFM 11.3% compared with 5.25%). A significant improvement in spasticity and range of movement was noted in the SPR + PT group compared with the PT only group. The weakness is most marked immediately after SPR. In this study the change in quadriceps strength from baseline to nine months was the same for patients treated with SPR plus PT as for those receiving PT alone (Steinbok et al. 1997a).

Chicoine et al. (1997) reported on the rates of orthopaedic surgery after SPR in 178 children reviewed with an average follow-up of 44 months (range 24-70). The patients were stratified into two age groups, those between two to four years and those aged five to 19 years at the time of the SPR. The overall rate of surgery was 17 %, significantly lower than previously reported. The rates of ankle and foot procedures, femoral osteotomy and iliopsoas recessions were no different, although the younger group had a significantly lower rate of heel cord, hamstring or adductor surgery. They concluded that SPR might reduce the need for subsequent orthopaedic operations. Unfortunately the data included surgery performed before and shortly after rhizotomy. Additionally the average age at the time of review was seven years, which is too young to determine actual rates to skeletal maturity (Chicoine et al. 1997).

6.2. Electrical stimulation (ES)

6.2.1 History of neuromuscular electrical stimulation

Treating diseases with electricity has been used for centuries. Electricity was used in the 17th century to describe the force which tingled the senses and moved the limbs (Gersh 1992, Baker et al. 2000). It was not until 1791 that published reports linked muscle contraction to the electrical stimulation of nerves. Galvani observed that the application of dissimilar metals to nerves innervating the muscles of the frog induced muscle contraction. Galen had divided nerves into sensory and motor classifications and, in 1822, Magendie made a formal distinction between them. This led to the first experiment with “electropuncture”, in which electric current was applied to needles inserted into muscles and nerves, a process similar to Japanese acupuncture (Baker et al. 2000).

Duchenne de Boulogne continued to explore the use of electropuncture in the 1830s and his design comprised cloth-covered, transcutaneous electrodes and a method of “localized electrization” over specific areas of muscles (Gersh 1992). Because he was the first person to use surface electrodes, he is known as the “father of electrotherapy” (Baker et al. 2000).

The introduction of electricity into muscles was recommended as a diagnostic tool in the mid- to late- 17th century. Several investigators noted that paralysed muscle responded to continuous electric current with steady output known as galvanic current but not to alternating current known as faradic current. It was also noted that if a continuous current was rapidly interrupted, creating an effect of a series of short duration pulses, no contraction was produced by a stimulated muscle when the interruptions exceeded a certain rate. From this, the conclusion was drawn that the duration of the current was the decisive factor in eliciting contraction (Baker et al. 2000).

In 1909, Lapicque named the threshold of excitation “rheobase”, which is defined as the minimal amount of current required to achieve a trace contractile response in the presence of an infinitely long stimulus pulse. He called the minimal duration of current needed to excite the tissue at double the rheobase intensity the “chronaxie” (Gersh 1992, Baker et al. 2000).

It was not until 1916 that Adrian mapped strength-duration curves for healthy and diseased human muscle. He noted a significant shift in the curves for muscle with nerve regeneration and certain characteristic changes in muscle undergoing neural regeneration (Baker et al. 2000). Bordet observed that muscles with intact nerves adapted to stimuli which increased in intensity over a period of time, while muscles deprived of their nerve supply did not demonstrate this property (Gersh 1992, Baker et al. 2000). The difference in the accommodation of innervated and denervated muscle became the basis of two electrodiagnostic tests, the galvanic twitch-tetanus ratio and the progressive current ratio (Baker et al. 2000).

In the 20th century, with an increased understanding of ES and such improved devices as the battery and the induction coil, enthusiasts of electro-therapeutics searched for diseases to cure. The treatment of peripheral nerve injuries grew during World War II with the development of clinical stimulators which were able to generate stimuli capable of exciting both denervated and partially innervated muscles (Gersh 1992).

The concept of NMES to provide the functional use of limbs was demonstrated by Liberson in 1961. He used a single channel of stimulation; ankle dorsiflexion was triggered with a foot switch during the swing phase of gait, thereby correcting the patient's foot drop (Gersh 1996).

6.2.2 Neurophysiological bases for application of neuromuscular electrostimulation (NMES)

6.2.2.1 Nerve fibres

The excitability of nerve and muscle provides the basis for the therapeutic use of electrostimulation (Baker et al. 2000). The peripheral nerves consist of motor axons or fibres and of sensory axons. In the spinal cord and brain stem, there are three types of alpha motoneuron whose axons innervate the muscle fibres that make up motor units. The motoneurons with the largest cell body and axons innervate fast glycolytic muscle fibres in fast-fatigable motor units. The motoneurons with a medium-sized cell body and axons build up fast fatigue-resistant motor units with fast oxidative glycolytic fibres, while the smallest motoneurons innervate slow-type motor units with slow oxidative muscle fibres (Kandel et al. 1995). Generally speaking, ES does not directly stimulate skeletal muscle. ES actually excites the motor nerves going to muscle and not muscle itself (Petrofsky 2004).

Once a nerve has been excited and depolarised, an action potential (AP) can be measured. The conduction of the AP and chemical synaptic transmission involves the same processes of neurosecretion and chemoreception, regardless of the mechanism of the original excitation. Transcutaneously applied ES may produce a muscle contraction similar to that produced by voluntary, physiological activity (Kandel et al. 1995, Baker et al. 2000). Physiological muscle activity differs from NMES activation primarily in recruitment order and the syncronicity of excitation of individual motor units. In physiological activity, small motoneurons with slow-fatiguing motor units are generally excited at low levels of contraction, followed by the recruitment of larger, more powerful units which fatigue more rapidly. With peripherally applied ES, the first units to fire are the large motoneurons, especially those supplying the large, fast and often more easily fatigable motor units. The smaller, slower motor units, which are metabolically capable of more prolonged contraction without fatigue, are excited only when stimulus intensity is increased (Kandel et al. 1995, Baker et al. 2000).

The afferent fibres of peripheral nerves can be classified according to their diameter and conduction velocity. There are four types of muscle afferent axon: large myelinated (type Ia and Ib), small myelinated (type II), smaller myelinated (type III) and unmyelinated (type IV) fibres. Another nomenclature, A alpha, A beta, A delta and C, is also used (Kandel et al 1995). The numerical classification is typically used for muscle afferents, while an alphabetical scheme is used for cutaneous nerves.

Group 1 (A alpha) afferents are absent in cutaneous nerves and virtually all axons coming from cutaneous mechanoreceptors are A beta fibres, whereas axons of thermoreceptors and nociceptors belong to the A delta and C groups (Kandel et al. 1995, Baker et al. 2000). Various characteristics of these fibre types are listed in **Table 5**a (Baker et al. 2000).

When ES is applied to peripheral nerves, the largest fibres (sensory Groups I & II) will be excited first. The motor fibres are excited along with sensory fibres, if the parameters exceed the thresholds of excitation. Because the sensory fibres are located in the skin, closest to the electrode, they will almost always be activated by a peripherally applied stimulus first, long before motor activation occurs.

Beyond the conventional ES response, weak electrical stimulations can evoke an itching sensation. The fibres that produce this response are newly found, low-threshold mechanosensitive C-fibres (Ikoma et al. 2005).

Table 5a. Mammalian Nerve Fiber Types and Characteristics (adapted from Baker 2001)

Fiber type .	Fiber diameter (µm)	Conductionn Velocity (m/sec)	Spike Duration (msec)	Absolute Refractory Period (msec)	Peripheral Organ	Receptor Organ	Function
A fibers (motor) alpha gamma	12-20 3-6	70-120 15-30	0.5-1	0.4-1	Muscle		Somatic motor Motor to muscle spindle
A fibers (sensory) Group Ia Group Ib	12-20	70-120	0.4-0.5	0.4-1	Muscle	Annulospiral spindle endings Tendon organs of Golgi	Proprioception
Group II beta	5-12	30-70	0.4-0.5	0.4-1	Flexor & Extensor muscles	Flower spray of spindle Touch-pressure receptors	Proprioception, touch, pressure, vibratory receptors
Group III delta	2-5	12-30	0.4-0.5	0.4-1	Skin Muscle	Unknown- pain receptors Pain	Pain- (fast), temperature
B fibers	1-3	3-15	1.2	1.2	Skin		Preganglionic sympathetics
C fibers Group IV	0.5-1	0.5-2	2	2	Muscle, skin and viscerae	Pain	Pain- (slow) temperature, mechanoreceptors

6.2.2.2 Physiological principles of ES

In an electrical circuit which interfaces with a physiological system, there will always be a minimum of two contacts (electrodes) between the stimulator and the physiological tissue. At the electrode-tissue interface, a conversion occurs between the current of electrons driven through the wires coupling the electrodes to the external stimulator, and the current of ions moved within the physiological system. At the positive electrode, termed the "anode", positive ions in the electrolytic interface and the underlying tissue are repelled, while negatively charged ions are simultaneously attracted. The other electrode, the negatively charged "cathode", acts as an attraction for the migrating positive ions and a repellent to negative ions.

Relative to excitable physiological tissue, the ions of particular interest are potassium and sodium, since the concentrations of these two ions are what cause both resting potentials and action potentials (Kandel et al. 1995, Baker et al. 2000). In the migration of positive and negative ions the resting cell membrane is excited principally under the cathode electrode (membrane depolarisation) and leads to hyperpolarisation near the anode electrode. The negative electrode is often used to evoke the muscle contraction and is termed the "active" electrode, because depolarisation of the biologically excitable tissue is most easily accomplished at the cathode. Excitable tissue under the positive electrode is less prone to depolarisation and thus, as a result, the anode is often termed the inactive, reference electrode (Gersh 1992).

Impedance (Z) is described as the combined effect on the electrical current passage of resistance, capacitance and inductance, measured in ohms at a particular test frequency. In physiological systems, impedance describes the ratio of voltage to current more accurately than resistance, because it includes the effects of capacitance and resistance. It is defined by Ohm's Law: V=IR or I=V/R, where V is the voltage output of a stimulator, driving a current (I) of ions through the tissue resistance (R) (Kandel et al. 1996, Baker et al. 2000) Current density is greatest near the electrode-skin interface and decreases with the distance from electrodes. The epidermis, bone and adipose tissue have high electrical impedance and tend to reduce current density in deeper tissues. Electrode positioning plays a major role in determining whether there is adequate current to create the desired depolarisation at a particular point.

6.2.2.3 Electrodes: size and orientation

Electrodes themselves play a major role in determining the effectiveness of electrical stimulation and the ease with which it can be given. Electrodes can be reusable or for single use. Carbon impregnated silicon rubber electrodes are reusable but generally require saline gel for conductivity and a moderate time for application and are not as convenient as the newer, synthetic, self-adhesive electrodes. The latter are those manufactured with both conductive and adhesive capabilities (Gersh 1992, Baker et al. 2000).

When electrodes are placed close together, most of the current passes through surface tissue. Electrodes spaced further apart facilitate the stimulation of deeper tissue. Electrode size is also important in determining current density. When using a constant current stimulator, the same total current is passed, even when electrode size is varied. The current density is therefore increased as the size of the electrode is reduced. Electrode size must be determined by the size of the muscle, the location of its motor points, and the size of the individual.

6.2.2.4 Pulse characteristics and parameters used during stimulation

Two types of current are used in electrotherapy: direct current (DC) and alternating current (AC). A direct current is one in which the flow of electrons is in one direction only. This current may be constant or continuous but varying in direction. DC can be delivered in pulse form. AC is

one in which the current flows first one way and then another as siniform waves or pulses (Gersh 1992).

Faradic stimulation (AC) consists of pulses which have a biphasic waveform and a pulse duration which is typically 0.3 msec. The pulse duration is always below 1 msec and the pulse repetition is less than 100 Hz (Gersh 1992).

Pulse duration, sometimes known as pulse width (expressed in microseconds, usec), is defined as the time taken for the instantaneous value of a pulse to rise and fall to a specified fraction of the peak value - that is, the duration of the output pulse at 50% of the maximum amplitude. The frequency of the stimulus train, the inter pulse interval, is the time between the start of one pulse and the start of the next. This is usually given in Hz and is actually the pulse repetition frequency when the space ratio is constant. The duty cycle of the stimulator comprises an "on time" reflecting the duration of pulse delivery and an "off time", the duration of recovery and quiescence. The total duty-cycle time is the sum of the "on and off times" (Gersh 1992, Baker et al. 2000).

6.2.3 NeuroMuscular Electrical Stimulation (NMES)

Neuromuscular electrical stimulation (NMES) is the transcutaneous application of electrical current to innervated, superficial muscle to stimulate muscle fibres, augment muscle contractions, increase range of motion (ROM) and enhance sensory awareness. The term NMES has been officially identified with the external control of innervated, but paretic or paralytic muscles by the electrical stimulation of the corresponding intact peripheral nerves (Electrotherapeutic Terminology in Physical Therapy, 1999).

The purpose of this external activation is to achieve a reduction in impairments and an increase in voluntary functional activities. In general, NMES has been applied so that the motor threshold is exceeded (high intensity) for a short period of time (15-60 minutes) (Baker et al. 2000). When the specific goals of therapy entail functional and purposeful movements, the specialised term functional electrical stimulation (FES) is applied. FES is therefore a subset of treatment programmes within the more broadly defined term NMES (Kitchen 2002, Baker et al. 2000). Subsensory or sensory threshold electrical stimulation which evokes sensations of itching or gentle tapping has been used to improve the awareness of the affected limb in adults with stroke and children with CP (Golaszewski et al. 1999, Tarkka et al. 2000, Brown et al. 2000).

Threshold electrostimulation (TES) differs from NMES by being administered on a subsensory or sensory level (low intensity) for a longer period of time (overnight for eight to 12 hours). TES was first used in children by Pape, who developed a programme for the treatment of disuse muscle atrophy in ventilator-dependent newborn infants. She subsequently also used a similar protocol in children with CP (Pape et al. 1993).

6.2.3.1 Clinical use in adults

In clinical settings both motor and sensory threshold NMES has been used for restoring ambulation and hand function in paralysed individuals suffering from stroke, spinal cord injury or other neurological conditions (Petrofsky 2004). Numerous studies have also suggested that NMES reduces spasticity and enhances the muscle strength of the hemiparetic limb (Levin and Hui-Chan 1992, Baker et al. 2000, Dimitrijevic et al. 1996, Glanz et al. 1996). Hesse et al. (1998) investigated in a randomised, placebo-controlled study with four treatment groups whether the combined approach of botulinum toxin type A (BtxA) and ES was more effective than the toxin alone in the treatment of chronic upper limb spasticity after stroke. Twenty-four stroke patients with chronic upper limb spasticity were divided into four different treatment groups (six patients in each treatment group), (A) 1000 units BtxA (Dysport) + ES, (B) 1000 units BtxA (C) placebo + ES, and (D) placebo. In groups A and C, additional ES of the injected muscles was given with surface electrodes, three times half an hour a day for three days. Muscle tone was rated with a modified Ashworth score, limb position at rest and difficulties encountered during three upper limb motor

tasks assessed before and two, six and 12 weeks after injection. In the results, most improvements were observed in patients in group A. Cleaning the palm task ($p=0.004$) differed across groups. Pairwise comparisons for this target variable showed that group A differed from groups B and D ($p<0.01$), but not from group C. Indicative across-group differences were obtained for elbow spasticity reduction ($p=0.011$) and putting the arm through a sleeve ($p=0.020$). The authors concluded the placebo-controlled trial favours the concept that electrical stimulation enhances the effectiveness of BtxA in the treatment of chronic upper limb flexor spasticity after stroke (Hesse et al. 1998).

Potisk et al. (1995) evaluated the effect of afferent cutaneous ES of spasticity of the leg muscles in patients with chronic hemiplegia after stroke (Potisk et al. 1995). They used a higher intensity of sensory level stimulation using a TENS unit with a different waveform. The stimulation was applied over the area of the sural nerve of the affected limb at 100Hz. In 18 of 20 patients a mild yet statistically significant reduction in resistive torques at all frequencies of passive ankle movements was recorded following 20 minutes of TENS application. The decrease in resistive torque was often (but not always) accompanied by a decrease in reflex EMG activity. This effect of TENS persisted up to 45 minutes after the end of TENS. The results of the study support the hypothesis that TENS applied to the sural nerve may induce a short-term post-stimulation inhibitory effect on the abnormally enhanced stretch reflex activity in spasticity of cerebral origin (Potisk et al. 1995).

Dewald et al (1996) studied adult subjects with hemiplegia. In this open study, the stimulation was performed over the area of the biceps muscle at an intensity level well below the motor threshold but just above the sensory threshold. They used a frequency of 20 Hz with a 0.1 ms pulse for a period of 10 minutes. This short exposure produced a measurable reduction in spasticity for at least 30 minutes following the electrical stimulation (Dewald et al. 1996).

Tarkka and Pitkänen (2001) carried out a blind controlled study on adult stroke patients (mean age 56 years) and demonstrated that distal sensory stimulation (glove electrostimulation) below the level needed to feel the stimulus (subsensor level) caused sensory evoked potential (SEP). This was interpreted as an activation of the sensory cortex (Tarkka and Pitkänen 2001).

In 2002, Peurala et al. investigated the influence of cutaneous stimulation for the enhancement of sensorimotor function in chronic stroke. Fifty-nine patients with chronic stroke received cutaneous stimulation during their three-week-long inpatient rehabilitation. Thirty-two patients received active treatment in the paretic hand and eight received no-current placebo treatment in the paretic hand. Nineteen patients received active stimulation of the paretic foot. None received stimulation in both upper and lower limbs. Cutaneous stimulation was delivered twice daily via a special glove/sock electrode. The modified Motor Assessment Scale, 10-metre walking test, paretic limb function, limb skin sensation and sensory evoked potential were performed before and after the treatment. All these outcome measures showed significant improvements in the treatment group ($n=51$) after three weeks of stimulation. When active hand treatment and placebo hand treatment were compared, a significant improvement in the sensory and motor function was only observed in the active treated group. These studies have shown that cutaneous stimulation had positive effects on the motor performance, limb sensation and the configuration of sensory evoked potential of paretic limbs in chronic stroke patients (Peurala et al. 2002).

6.2.3.3 Clinical use in CP

ES as a treatment option for CP has been proposed after several studies in recent years (Carmick 1993a,b, Hazlewood et al. 1994, Pape et al. 1993, Steinbok et al. 1997b).

Because of the variation in application methods, it is important to distinguish between the various types. First, in the traditional manner, the ES can be applied therapeutically for shorter durations and at the intensity sufficient to cause contraction of the muscle (Hazlewood et al. 1994, Wright and Granat 2000, Comeaux et al. 1997). Alternatively, the stimulation can be applied in a

functional situation as an add-on therapy, stimulation is triggered to assist in a functional activity (Cracanin 1984, Carmick 1993a,b). A third way is to apply the stimulation at a low intensity, below contraction level, for several hours during the night (Pape et al. 1993, Steinbok et al. 1997b, Sommerfelt et al. 2001).

6.2.3.4 Traditional NMES studies

Dubowitz et al. (1988) applied ES to the tibialis anterior of two children with hemiplegia while they were active. They reported an increase in maximum voluntary contraction during ankle dorsiflexion and a subjective improvement in motor performance and gait. The effect of electrically stimulating the anterior tibial muscles of children with hemiplegic CP was studied by Hazlewood et al. (1994). Ten children received NEMS, applied daily for an hour for 35 days by their parents at home. Ten children acted as controls. During the stimulation, the intensity of which was set to cause dorsiflexion, the children had no scheduled therapy. The children were assessed prior to the treatment and the outcome was assessed between six and 12 weeks later (mean nine weeks). There was a significant increase in the passive range of dorsiflexion of the children receiving electrical stimulation. There was also a significant increase in the power of the tibialis anterior muscle in the stimulated group. The power was estimated using the Medical Research Council grades of muscle power (Hazlewood et al. 1994). Comeaux et al (1997) used gait analysis in 14 children with CP to study NMES given for 15 minutes to the gastrocnemius or gastrocnemius- /tibialis anterior muscles of children during scheduled gait and/or functional activity. The children received no other PT during this experiment, in which each period was four weeks, including the pre-treatment and post-treatment periods. Both the stimulation treatments gastrocnemius only or gastrocnemius and tibialis anterior, improved heel-strike dorsiflexion. A randomised controlled study in 2001, by Park et al. described the effects of ES applied to the abdomen and posterior back muscles in young children aged eight to 16 months while sitting. After six weeks of ES therapy, changes in the kyphotic angle and the GMFM score for sitting were significantly higher in the stimulation group (n=14) than in the control group (n=12) (Park et al. 2001). Scheker and co-workers' (1999) retrospective study demonstrated that the use of neuromuscular electrical stimulation (NMES) combined with dynamic orthotic traction in the daytime and static orthosis through the night is a relatively quick and effective method for treating children with spasticity of the upper extremities due to CP. In an observational study of eight children with CP, Wright and Granat (2000) used a six-week treatment period consisting of single 30-minute daily sessions of cyclic functional ES and showed that hand function improved. The improvements were largely maintained until the end of the six-week follow-up period (**Table 5b**).

Table 5b. Parametres used in different studies

NMES	Author	Frequency (Hz)	Pulse duration	On:off (s)	Intensity (mA)	Session duration	Session frequency	Total Rx time (b(wk×mo)
	1. Dubowitz et al.	40	250 µ	-	Elicite effective dorsiflexion	1h	3/ day, daily	21h/wk×2mo
	2. Atwater at al.	20-100	0.3 or 1.0 ms	-	0-90	20min	3/ week	1h/wk×2mo
M	3. Carmick[1]	5-7 up to 30- 35	300 µs	10:25 up to 15:15 or operator control	Tolerance (no longer than 50 % machine maximum)	15-20 min	For 10 sessioms, or 1/week longer periods	0.25-0.33/wk×11mo
	4. Carmick[2]	5-7 up to 30- 35	-	10:25up to 15:15 or operator control	Tolerance (no longer than 50 % machine maximum	15-20 min	For 10 sessioms, or 1/week longer periods	0.25-0.33h/wk×6mo
	5. Carmick[3]	-	100 µs	7:15	Dorsiflexion short of passive time	1h		
	6. Carmick[4]	7 up to 10 (35)	-	-	-	-	Daily	7h/wk×1mo
E	7. Hazlewood et al.	30	300 µs	15:15 or operator control	Tolerance	15min	For 8 sessions or more	-
	8. Comeaux et al.	32	-	operator control	Visible contraction	15 min	With therapy for 26mo	0.25h/wk×26mo
	9. Bestoti et al.	-	1-200 µs (ramped)	1:.5 (ratio)	20	15 min		0.75h/wk×1mo
	10. Wright and Granat	30	300 µs	10:10	10-40, maximum ROM without discomfort	30 min	3/ week	2.5h/wk×7-10mo
S	11. Park et al.	35	250 µs	10:12	25-30	30 min	2/ day, 5/ week	3.5h/wk×1.5mo
	12. Van der Linden et al	10 up to 30	75 µs ↑ to 100 µs	5:15	Patient tolerance	1h	Daily	3h/wk×1.5mo
T	13. Pape et al.	35- 45	300 µs	1:1 (ratio)	-	9h	Daily	63h/wk×6mo
	14. Steinbok et al.	35	300 µs	8:8	Less than 10	8-12h	6/week	48-72h/wk×12mo
E	15. Sommerfelt et al.	40	300 µs	-	Less than 10	At least 5/night	6/week	At least 30h/wk×12mo
S	16. Dali et al.	35	-	-	1-5	At least 5/night	6/week	At least 36h/wk×12mo

1= 1993a ; 2= 1993b ; 3= 1995 ; 4= 1997

6.2.3.4 Stimulation as an add-on therapy

Children with early acquired motor deficits often have difficulty producing selective movements in an affected extremity and it has been suggested that this is due to a form of developmental apraxia caused by defective motor planning in early infancy (Brown et al. 2000, Beck 1997). Daytime stimulation aims to provide feedback to the brain about the muscles that are activated during therapy. Stimulation at sensory level helps the child to "localise" the muscle he/she is trying to use. The feedback information from the child's own movements facilitates motor learning (Pape et al. 1993, Larin 1997, Reed 1997). ES applied transcutaneously at an intensity sufficient to evoke a perception analogous to a "tapping" or "tickling" feeling is presumed to activate large sensory nerve fibres (Gersh 1992). The stimulation is applied so that the child is able to detect a sensation, but a muscle contraction is neither visible nor palpable. It is hypothesised that this kind of sensory stimulation increases the awareness of the involved extremity, thereby improving function (Beck 1997, Pape 1997). As a result, ES at sensory level administered at an amplitude lower than that resulting in a muscle contraction may be an attractive treatment alternative, especially in children who do not tolerate NMES well (Carmick 1993a, b, Beck 1997, Pape 1997). In 1993, Carmick reported on the clinical use of NMES in children with CP. She used ES as an add-on therapy so that it first gave a tapping sensation and sensory input without causing a fused contraction. When this sensation was tolerated by the child, the setting was increased to give fused muscle contractions. She analysed the functional changes that occurred following the application of NMES to the lower extremities of three boys, aged 1.6, 6.7 and 10 years. The youngest child displayed an immediate improvement in his ability to walk and run symmetrically. The two older boys demonstrated a significant increase in locomotor efficiency. One boy's Physiological Cost Index (PCI) measurement improved fourfold, while the other boy's PCI improved twofold (Carmick 1993a).

Carmick (1993b) demonstrated that two children with hemiplegia, 1 year 7 months and 6 years 9 months old, quickly learned to use their affected hands when NMES was added to the PT programme (Carmick 1993b). NMES has been used particularly for muscle re-education and strengthening where the stimulation is designed to create a motorneuronal response resulting in a muscle contraction (Carmick 1993a,b, Baker et al. 2000) (**Table 5b**).

6.2.3.5 Threshold electrostimulation (TES)

Threshold ES (TES) differs from NMES by being administered at the subsensory or sensory level (low intensity) for a long period (overnight for eight to 12 hours). TES was first used by Pape et al., who developed the programme for the treatment of disuse muscle atrophy in newborn infant who was ventilator dependent. In 1993, Pape et al. conducted an open study in which subsensory TES was applied overnight for six months in patients with mild CP and they noted a statistically significant improvement in function. At follow-up, after the children had been without TES for six months, there was a uniform loss of scores (Pape et al. 1993). Steinbok et al. (1997b) have reported the results of a trial of TES in children with muscle weakness persisting after SPR (Steinbok 1997b). The study was designed as a randomised controlled, single-blind trial that was carefully stratified by ambulatory status. The key outcome variable was functional improvement measured by the GMFM. A power analysis was performed and it was determined that 22 subjects in the study and the 22 subjects in the control group would be required to demonstrate a significant change in the key outcome variable. Importantly, the selection criteria were clearly delineated. All the children had undergone SPR more than one year prior and had not undergone any surgical procedure affecting lower limb function in the previous twelve months (Steinbok 1997b).

Contradictory results were obtained by Sommerfelt et al. (2001) and Dali et al. (2002). In a randomised cross-over study over 24 months, Sommerfelt et al. (2001) evaluated the effect of TES

applied to the antagonists of the spastic leg muscles in 12 children (age range 5-12 years) with spastic diplegia and they were unable to show any significant effect of TES on motor or ambulatory function. The authors of this study concluded that "no significant effect of TES on motor ambulatory function was found on the blinded evaluation of motor function but parents of 11 of the 12 children studied stated that TES had had a significant effect". The authors concluded that the "weaknesses were that the sample size may be insufficient to detect a real effect of the treatment and that the main methods used for evaluation have not been validated". The strengths of the study were the blinded assessment, the cross-over design and the extended treatment and control periods (Sommerfelt et al. 2001). In a randomised, double-blind placebo-controlled study by Dali et al. (2002) of 57 children with CP (age range 5 to 18 years), the use of TES for 12 months failed to produce any significant effects (Dali et al. 2002) (**Table 5b**).

Recently, McDonough et al. (2003) presented data from a study of 60 children with CP (ages five to 16 years) who were randomised into three groups to 1) receive NMES (15 minutes 5 days a week), 2) TES (overnight 5 days a week), and 3) physical therapy. The duration was four months, and the strengthening of the quadriceps was the goal of the therapy. Assessment by GMFM and lifestyle assessment questionnaire revealed that TES and NMES were significantly superior to PT (McDonough et al. 2003).

6.2.4 Physiological background of microcurrent electrostimulation (MENS)

Microcurrent or low-intensity DC stimulation works at microampere level and thereby mimics the electrical intensity found in the living tissues. The earliest experience of microcurrent treatment was obtained from its effects on tissue damage healing (Cheng et al. 1982). It is assumed that, when this kind of current is administered to injured or malfunctioning tissue it can restore the abnormal electricity of injured or malfunctioning cells (Baker et al. 2000). Becker and Selgon (1985) hypothesised that a bioelectric direct current, produced by injured tissue, was conducted via the Schwann and central nervous system glial cells to the brain stem and back to the area of injury, thereby triggering tissue repair and regeneration. Tissue electricity, wound currents and the capacity of glial cells to propagate non-actiopotential-like signals have been demonstrated. On these bases, Becker presented a theory that low-intensity DC electrotherapy can mimic the repairing action of the body current (Becker and Selgon 1985). Because of its galvanotaxis, which is described as the migration of fibroblasts and macrophages, microcurrent can make these cells move to the injured area and promote healing (Demir et al. 2004).

Microcurrent could also function as a mild mechanical stimulus and act on cell membrane receptors which are sensitive to mechanical forces such as pressure and stretching. It has been shown in vitro that mild mechanical stimuli affect the mechanosensitive cell membrane receptors (e.g. integrin-family) more effectively than strong forces (Wang et al. 2001). The activation of mechanosensitive receptors leads to the influx of calcium ions and ultimately to the activation of mitochondrial ATP syntheses (Seegers et al. 2002).

Microcurrent therapy could also affect the state of the whole body by activating low threshold mechanosensitive C-axons in the skin. These axons do not react to thermal or nociceptive stimuli but to gentle touch or pressure. The information from these axons of this kind goes through the spinal cord and the thalamus to the insula. Feelings of pleasure and relaxation are the result of the stimulation of C-axons (Olausson et al. 2002). It has been shown that high-frequency (80 Hz), low–intensity (0.4mA) TENS stimulation can affect regional blood flow in cortical areas to which the low threshold mechanosensitive C-axons send signals (Johansson et al. 2001b). Because low-intensity alternating current (TENS) can produce these effects, low-intensity direct current (MENS) stimulation can also be expected to activate these axons, although it is not capable of depolarising thicker sensory (or motor) axons (Olausson et al. 2002).

Several animal studies have demonstrated that low-intensity current electrotherapy improves the healing of tendons and ligaments (Akai et al. 1997, Lin et al. 1997, Nessler and Mass 1987, Dunn 1988, Cheng et al. 1982). Dunn (1988) studied growing fibroblasts in the collagen matrix of an experimental skin wound in the guinea pig. He showed that fibroblast in-growth and collagen-fibre alignment were promoted by direct current microampere stimulation. The currents used in this experiment varied from 20 to 100 μA, with the maximum fibroblast growth response observed near the cathode (Dunn 1988). Similar results were obtained by Erickson and Nuccitelli (1986) using fibroblasts from the quail embryo (Erickson and Nuccitelli 1986). The enhancing effects of microcurrent therapy on wound healing have been demonstrated by several authors (Nessler and Mass 1987, Picker 1985 a, b).

Weiss et al. (1989) compared scar thickness and hypertrophic scar formation at the skin graft donor site in four patients. Each patient had bilateral split skin grafts taken from the anterior thigh. Pulsed direct current (150 μs) was given, while the other side acted as a control. The electrostimulation started on the day of surgery and consisted of two daily 30-minute sessions for seven days. The findings strongly suggested that the scars at the donor sites which had been subjected to ES were softer, flatter and cosmetically more acceptable. The biopsy data support the subjective (blinded) findings, as the thickness of the treated scars was 46% on average of the thickness of the untreated scars. The biopsies also revealed fewer mast cells in the stimulated scars (Weiss et al. 1989). The effect of ES under these conditions suggests that it can reduce fibrosis, probably by reducing the number of inflammation-supporting mast cells.

The effect of microcurrent therapy on fibrosis was documented by Lennox et al. in 2002. The purpose of their study was to evaluate the effectiveness of impedance-controlled microcurrent stimulation in managing radiation-induced fibrosis in head and neck cancer patients. After one week's therapy, the cervical rotation range of motion changed from the baseline of 59 degrees to 83 degrees. The flexion/extension improved from 47 degrees to 73 degrees and the lateral flexion changed from 31 degrees to 48 degrees (Lennox et al. 2002).

Cheng et al. (1982) studied the effects of electric currents of various intensities on three variables critical to the healing process: adenosine triphosphate (ATP) generation, protein synthesis and membrane transport. At 500 μA, ATP generation in rat skin increased by almost 500 per cent. Between 1,000 and 5,000 μA (1-5mA), ATP generation nose-dived and at 5,000 μA, it dropped below baseline control levels (Cheng et al. 1982). A very similar picture emerged with respect to amino acid transport and protein synthesis. Amino acid transport was increased by 30 to 40 percent above control levels using 100 to 500 μA. When the current was further increased to exceed 1,000 μA, these biostimulatory effects were reversed (Lennox et al. 2002). Recently, a low direct current electric field has been shown to increase the amount of ATP in HeLa cells (in vitro) by 163 % (Seegers et al. 2002).

6.2.4.1 Clinical use of MENS

In a pioneering prospective, randomised comparative study of microcurrent treatment for chronic Achilles tendinopathy by Chapman-Jones and Hill (2002), 48 adult subjects were assigned to either group A, exposed to current clinical management, or to group B, the experimental microcurrent electrical stimulation regimen. The subjects in group B received 30 minutes of microcurrent treatment daily for 14 days. An evaluation of the parameters of pain and stiffness revealed that the general assessment score showed statistically-significant differences ($p<0.001$) in favour of treatment B in all three of the markers used. The most progress was made during the first three months after the treatment, after which it was maintained or deteriorated minimally (Chapman-Jones and Hill 2002).

Microcurrent stimulation has been shown to be effective in chronic Achilles tendinopathy and this kind of treatment could therefore also be valuable in children with CP. The present study was

designed to determine whether MENS increases the range of motion of the ankle joint in children with CP.

6.3 Methods used for assessment of CP

The most commonly used assessment tools are listed below (**Table 6**).

Table 6. The assessment tools used for CP

The evaluation of function or locomotion
Gross Motor Function Measurement (GMFM) (Russel et al. 1993)
Gross Motor Function Classification Scale (GMFCS) (Palisano et al. 1995)
Goal attainment scaling (GAS) (Palisano 1993)
Physiological Cost Index (PCI) (Carmick 1993a)
Gait analysis/laboratory (Gage 2004)
Modified Ashworth scale of muscle spasticity (Bohannon and Smith 1987)
Muscle Testing (Daniels and Worthingham 1972)
Range of Motion (ROM) (Cadenhead et al. 2002)
Upper extremity only
The Melbourne Assessment (5 years of age and over) (Randall et al. 1999)
The Assisting Hand Assessment (AHA) (Krumlinde-Sundholm and Eliasson, 2003)
Box and Block Test of Manual Dexterity (6 years and over) (Mathiowetz et al. 1985)
King hypertonicity scale (King 1987)
Zancolli classification (Zancolli et al. 1983)

7. AIMS OF THE STUDY

The objective of this thesis was to investigate the impact of less commonly used rehabilitation methods in children with cerebral palsy.

The specific aims were:

1. To compare the impact of SPR combined with postoperative intensive PT and with PT alone on spasticity and motor function in children with CP in a five year follow-up (I)

2. To investigate the effect of sensory-level ES of the tibial anterior muscle during physical therapy sessions as an add-on therapy enhancing ankle dorsiflexion (II)

3. To investigate whether the use of sensory-level ES on the wrist dorsiflexors and infraspinatus in the affected upper extremity in children with hemiplegic CP could improve the function of the upper extremity (III)

4. To investigate whether microcurrent stimulation (MENS) increases the range of motion of the ankle in children with CP (IV)

8. PATIENTS AND METHODS

8.1 Patient series and study design

The Department of Child Neurology at the Helsinki University Central Hospital is the secondary and the tertiary referral unit for a population of 1.4 million people living in the catchment area of this hospital. All the children with CP in the city of Helsinki (pop. 560, 000) are followed at this unit and all the children with CP who are primarily followed at the hospitals in this area for whom treatment other than physiotherapy is considered are referred to this unit. In addition to this, children with CP are referred to this unit from other parts of the country for special reasons, such as SDR and multilevel surgery. The patients recruited for the studies were selected from these patients in regular follow-up according to the criteria described below.

The study of rhizotomy was a retrospective, comparative, five-year follow-up study (I). The open, uncontrolled studies of sensory level electrostimulation on the upper extremity and the microcurrent study were A-B-A type studies (III, IV) and the study of sensory level electrostimulation on the lower extremity was a B-A-A type study (II). B indicates the intervention period and A prior to B indicates the baseline period, whereas A after B means the follow-up period.

The study designs were approved by the ethics committees at the Children's Castle Hospital and University Central Hospital of Helsinki.

8.2 Inclusion criteria and therapeutic methods

8.2.1 Selective Posterior Rhizotomy (SPR) (I)

A total of 44 children with CP were referred to the Helsinki University Hospital from the whole of Finland to be considered for SPR between April 1991 and September 1998. On the basis of a thorough multimodal preoperative evaluation, a total of 23 children were selected for SPR + PT and 21 children continued with the normal-intensity PT. We subsequently excluded two operated children as the diagnoses differed clearly from the general recommendation for SPR.

The children whose motor development progressed for at least six months were allocated to the group with normal-intensity PT. A description of the background factors of the study children and the mean value of the preoperative functional scales are shown in **Table 7**.

In all, 75% of the children undergoing surgery and 69% of the children not undergoing surgery were boys. Four of the children undergoing surgery had (spastic) quadriplegic CP, while two of the children not undergoing surgery had spastic quadriplegic CP.

The inclusion criteria for the SPR+ PT group:
The children were allocated to the two treatment groups on a clinical basis and not randomly. The inclusion criteria for SPR+PT were:
1. functionally disruptive spasticity in the lower limbs (diplegia),
2. at least six months' arrest of motor development and/or
3. spasticity-dependent difficulties in daily care (quadriplegia).

The inclusion criteria for the PT group were:
1. slow, ongoing motor development, hypotonia or severe weakness of trunk or lower limb muscles,
2. muscle contractures or rigidity
3. other reasons were lack of motivation for the SPR and poor social situation.

8.2.2 Sensory-level electrostimulation on affected lower extremity (II)

The inclusion criteria for the study were:

1. children with hemiplegic or diplegic CP,
2. age from three years to 11 years,
3. failure to make substantial progress using standard physiotherapy,
4. limited active dorsiflexion (defined as being less than the passive range or absence of selective active ankle dorsiflexion),
5. no botulinum toxin treatment for the past six months and/or
6. ability to co-operate during physical therapy sessions.

The first 17 children who fulfilled these criteria and were seen during a six-month period (1998 to 1999) were recruited for this study. The details are shown in **Table 7**. There were nine girls and eight boys and 11 of the children had hemiplegic CP. Two of the children with spastic diplegia used walking aids (tripod canes, ordinary canes). Six of the children wore hinged ankle orthoses, three wore dynamic ankle-foot orthoses and the other eight individuals wore foot orthoses.

8.2.3 Sensory-level electrostimulation on affected upper extremity (III)

The inclusion criteria for the study:

1. children with spastic hemiplegia,
2. aged 2 to 12 years at the time of referral,
3. no botulinum toxin treatment for six months prior,
4. weak extensors of wrist and elbow ($\leq$ 3 according to Daniels and Worthingham) in the affected upper extremity,
5. ability to co-operate during physical and/or occupational therapy sessions and/or
6. no previous hand surgery.

The first twelve children, who fulfilled these criteria and were scheduled for a visit during the six-month period in 1999- 2000, were recruited for this study. They were subdivided so that the first group (A) consisted of children under four years of age, while the other group (B) comprised children aged 4 to 12 years. The mean age was 2.9 years (range 2.1-3.95 years) in Group A and 8.8 years (range 6.4-11.9 years) in Group B. The details are shown in **Table 7**.

8.2.4. Microcurrent stimulation for Achilles contracture (MENS) (IV)

The inclusion criteria for the study:

1. children with hemiplegic or diplegic CP,
2. age: $\geq$ 4 years,
3. passive ROM of ankle: deteriorating or constantly subnormal (ankle dorsiflexion $\leq$ 0 degree, mid-position) with knee extended and/or ankle dorsiflexion $\leq$ + 5 degrees from mid-position with knee flexed), despite optimal physiotherapy regimen and/or splinting/night splinting/orthoses. Minimum duration of subnormal passive ROM $\geq$ 3 months,
4. other therapies: no effect from botulinum toxin treatment/not eligible for botulinum toxin treatment due to absence of dynamic component of ankle dorsiflexors or dynamic EMG finding ruling out a possible beneficial effect by botulinum toxin, no effect from previous surgery on the range of movement of the Achilles tendon, or deterioration in the results of surgery to a pre-surgery level,
5. participation: ability of the child and the family to cope with the study.

The participants in this study were selected from the entire series of children with CP followed at the department from October 2001 to June 2002. Of all the children seen in this period there were twelve children with spastic hemiplegia that fulfilled the above-mentioned criteria. Seven children had right-sided hemiplegia. All the children were independent community ambulators. Three of the children had previously had an elongation of the Achilles tendon. All of them had had their operations more than 18 months prior to the start of this study. The details are seen in **Table 7**.

Table 7. Patient series

Study	**I**		**II**	**III**	**IV**
	SPR+PT	PT	ES-LL	ES-UL	MENS
Number of patients	21	21	17/ 23	12	12
Mean age at assessment(y)	6	6	6.4	5.6	10.0
Range	3-11	3-14	3.8- 8.9	2-12	4.5- 16
No of boys/ girls	16/ 5	15/ 6	8/ 9	7/ 5	7/ 5
Type of CP*	D17, T4	D19,T2	H11, D6	H12	H12
Spasticity range (0-5)	4.2	3.9	Not measured	Not measured	Not measured
Mean Illinois St Louis	6.7	6.6	1.1	1.0	1.0
Mean GMFC scale	3.80	3.42	1.17	1.00	1.20

*D= diplegia
*H= hemiplegia
*T= tetraplegia

LL= lower limb
UL= upper limb

SPR= selected posterior rhizotomy
PT= physiotherapy
ES= elecrostimulation
MENS= micro electrostimulation

8.3. Methods used for assessment

8.3.1 The evaluation of locomotion, spasticity and muscle strength (I)

The function was evaluated using two different scales. The first evaluation was based on the Illinois-St Louis Scale, where an independent movement is scaled from 1 to 9 (1= independent walking and 9 = no purposeful movement) **(Table 8)** (Lundberg et al. 1993).

Table 8. The Illinois St Louis Scale

1	Independent walking
2	Walking, poor pattern
3	Walking with canes/ crutches
4	Walking with a rollator
5	Walking assisted
6	4- point crawling
7	Creeping, sitting alone
8	Minimal purposeful movement
9	No purposeful movement

The second method was the gross motor classification scale (GMFCS) which was evaluated retrospectively from study reports and clinical video or hospital records.

Distinctions between levels (Level 1 to 5) of motor function are based on functional limitation, the need for assistive technology including mobility devices (such as walkers, crutches and canes) and wheeled mobility and, to a lesser extent quality of movement (**Table 9)** (Palisano et al. 1995).

Assessment of spasticity (I)
Based on the Ashworth-Bohannon Scale, spasticity was graded from 0-5; with 0 as the lowest (no spasticity) and 5 as the highest value (Bohannon and Smith 1987).

Assessment of lower limb muscle strength (I)
This was rated from 0-5 (0 as the lowest and 5 as the highest value) according to Peacock (Peacock et al. 1987).

One-foot activities
Standing on one foot (II, IV)
Standing on one foot without support (seconds) was measured barefoot to eliminate variation caused by different types of orthosis.

The number of hops (II, IV)
The number of hops on one barefoot was counted. Hopping on both feet was examined in the children with spastic diplegia and only the affected foot in children with hemiplegia.

Table 9. Gross motor function classification scale (GMFCS) (Palisano et al. 1997)

Before 2nd birthday

Level I Infants move in and out of sitting and sit on the floor with their hands free to manipulate objects. Infants crawl on hands and knees, pull to stand and take steps holding on to furniture. Infants walk between 18 months and 2years of age without the need for any assistive mobility device.
Level II Infants maintain floor sitting but may need to use their hands for support to maintain balance. Infants creep on their stomach or crawl on their hands and knees. Infants may pull to stand and take steps holding on to furniture.
Level III Infants maintain floor sitting when the low back is supported. Infants roll and creep forward on their stomach.
Level IV Infants have head control but trunk support is required for floor sitting. Infants can roll to supine and may roll to prone.
Level V Physical impairments limit voluntary control of movement. Infants are unable to maintain antigravity head and trunk postures in prone and sitting. Infants require adult assistance to roll.

Between 2nd and 4th birthday

Level I Children sit on the floor with both hands free to manipulate objects. Movements in and out of floor sitting and standing are performed with assistance. Children walk as the preferred method of mobility without the need for any assistive device.
Level II Children sit on the floor but may have difficulty with balance when both hands are free to manipulate objects. Movements in and of sitting are performed without adult assistance. Children pull to stand on a table surface. Children crawl on hands and knees with a reciprocal pattern, cruise holding onto furniture and walk using an assistive mobility device as preferred methods of mobility.
Level III Children maintain floor sitting often by "W-sitting" (sitting between flexed and internally rotated hips and knees) and may require adult assistance to sit. Children creep on their stomach or crawl on hands and knees (often without reciprocal leg movements) as the primary methods of self mobility. Children may pull to stand on a stable surface and cruise short distances. Children may walk short distances indoors using an assistive mobility device and adult assistance for steering and turning.
Level IV Children sit on a chair but need adaptive seating for trunk control and to maximise hand function. Children move in and out of chair sitting with assistance from an adult or a stable surface to push or pull up on with their arms. Children may at best walk short distances with a walker and adult supervision but have difficulty turning and maintaining balance on uneven surfaces. Children are transported in the community. Children may achieve self-mobility using a power wheelchair.
Level V Physical impairments restrict voluntary control of movement and the ability to maintain anti-gravity head and trunk postures. All areas of motor function are limited. Functional limitations in sitting and standing are not fully compensated for by the use of adaptive equipment and assistive technology. At level V, children have no means of independent mobility and are transported. Some children achieve self-mobility and are transported. Some children achieve self-mobility using a power wheelchair with extensive adaptations.

Between 4th and 6th birthday

Level I Children get into and out of, and sit on, a chair without the need for hand support. Children move from the floor and from sitting on a chair to standing, without the need for objects for support. Children walk indoors and outdoors, and climb stairs. Emerging ability to run and jump.
Level II Children sit on a chair with both hands free to manipulate objects. Children move from the floor to standing and from sitting on a chair to standing but often require a stable surface to push or pull up on with their arms. Children walk without the need for any assistive mobility device indoors and for short distances and on level surfaces outdoors. Children climb stairs holding onto a railing but are unable to run or jump.
Level III Children sit on a regular chair but may require pelvic or trunk support to maximise hand function. Children move in and out of chair sitting using a stable surface to push on or pull up with their arms. Children walk with an assistive mobility device on level surfaces and climb stairs with assistance from an adult. Children are frequently transported when travelling for long distances or outdoors on uneven terrain.
Level IV Children sit on a chair but need adaptive seating for trunk control and to maximise hand function. Children move in and out of sitting on chair with assistance from an adult or a stable surface to push or pull up on with their arms. Children may at best walk short distances with a walker and adult supervision but have difficulty turning and maintaining balance on uneven surfaces. Children are transported in the community. Children may achieve self-mobility using a power wheelchair.

Between 6th and 12th birthday

Level I Children walk indoors and climb stairs without limitations. Children perform motor skills including running and jumping but speed, balance, and coordination are reduced.
Level II Children walk indoors and outdoors, and climb stairs holding onto a railing but experience limitations walking on uneven surfaces and inclines, and walking in crowds or confined spaces. Children have at best only a minimal ability to perform gross motor skills such as running and jumping.
Level III Children walk indoors or outdoors on a level surface with an assistive mobility device. Children may climb stairs holding onto a railing. Depending on upper limb function, children propel a wheelchair manually or are transported when travelling for long distances or outdoors on uneven terrain.
Level IV Children may maintain levels of function achieved before age 6 or rely more on wheeled mobility at home and school and in the community. Children may achieve self-mobility using a power wheelchair.
Level V Physical impairments restrict voluntary control of movement and the ability to maintain antigravity head and trunk postures. All areas of motor function are limited. Functional limitations in sitting and standing are not fully compensated for by the use of adaptive equipment and assistive technology. At level V, children have no means of independent mobility and are transported. Some children achieve self-mobility using a power wheelchair with extensive adaptations.

8.3.2 The Goal Attainment Scale (GAS) (II, III)

The overall effects of the add-on ES was assessed using the Goal Attainment Scale (Palisano 1993). For Studies II and III, the GAS criteria were as described in **Table 10**.

Table 10. The Goal Attainment Scale (Palisano 1993)

	Study I I	Study III
GAS 0	No change	No change
GAS 1	Significant increase in active selective dorsiflexion (5^{o}) with the knee flexed or extended	A twofold increase in the duration time supporting him/herself by means of the extended affected upper extremity in the crawling position
GAS 2	1 + additional active functions	1 + additional active functions
GAS –1	Significant decline (5^{o}) in active dorsiflexion	Significant decline in active arm extension or loss of a maximum of two active movements
GAS -2	1- and additional deterioration in function.	1- and additional deterioration in function.

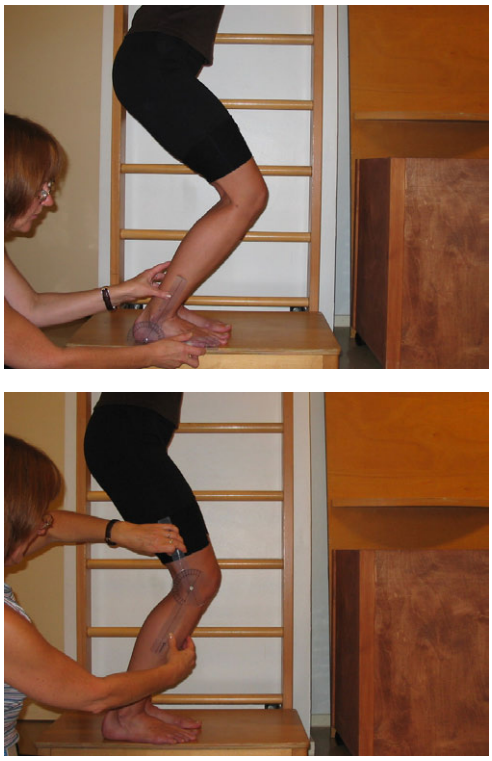
GAS measures the achievement of the goal set at the beginning of the treatment. In the second study (II), the assessment was made when the child was sitting with his/her feet hanging freely. In the third study (III), the assessment was made with the child in the crawling position with the unaffected hand lifted to the horizontal level so that the child was supporting him/herself on the affected extended arm.

8.3.3 The evaluation of range of motion (ROM)

8.3.3.1 Passive ROM (II, IV)

Passive ROM of ankle dorsiflexion (with the knee flexed and extended) was measured using manual goniometry. The child lay supine with the hip and knee extended or the hip and knee flexed at 90 degrees. The measurement of maximum passive ROM was made gently in order to minimise the velocity-dependent increase in the tonic stretch reflex (spasticity). The same two persons performed all the measurements so that the calcaneus was kept in the mid-position when the foot was manually and slowly dorsiflexed to its maximum. The mid-position (90^{o}) of the ankle was used as the baseline with the goniometer set at zero. The most representative measurement was recorded.

Picture 1. Measurement of the angles of the ankle and knee



The assessment of the ROM of the popliteal angle and ankle dorsiflexion during active flexion of the knees when standing was made with the patient placed standing on a wooden box (height 15 cm) with his/her heels in contact with the surface of the box. The patient was then instructed to flex his/her knees to the maximum while maintaining floor contact with the heels. The children were asked to support themselves on both feet as evenly as possible and to maintain their body alignment without any change. External support was only available to avoid falls. The moment at which heel-surface contact was lost was visually observed and goniometry of knee and ankle flexion was carried out. The most representative and technically optimal performance was recorded **(Picture 1**).

8.3.3.2 Active ROM (II, III)

Muscle function was tested in Studies II and III using a scale modified according to Daniels and Worthingham (Daniels and Worthingham 1972) (**Table 11a and 11b)**.

In the study II the child lay supine with the hip and knee extended or the hip and knee flexed to 90 degrees and the measurement of active ROM of ankle dorsiflexion was made using manual goniometry. The difference in active inversion, eversion, toe flexion, and toe extension was assessed with the child sitting with his/her feet hanging. This position enabled the children to see their feet, which helped them to perform the selective movement. Muscle testing was performed with the child sitting on a chair. The functions tested in the study III were supination and dorsiflexion of the wrist **Table 11b**.

Table 11a. Scores used in Study II (Daniels and Worthingham 1972)

0 = no visible activation on request
1 = visible contraction without active movement
2 = visible active movement less than available passive ROM
3 = visible active movement equal to available passive ROM.

Table 11b. Scores used in study Study III (Daniels and Worthingham 1972)

0 = no visible activation upon request
1 = visible contraction without active movement
2 = visible active movement < mid-position
3 = visible active movement >mid-position < passive ROM
4 = visible active movement = passive ROM

8.3.4 Zancolli classification (III)

The Zancolli classification was used to assess hand function. This measurement was originally developed to evaluate wrist and fingers after brain damage or cervical spinal cord injuries (Romain et al. 1999, Yoshimura et al. 1998), but it is also used nowadays by occupational therapists to evaluate the outcome of hand surgery (Zancolli et al. 1983) (**Table 12**).
This classification test was administered with the child sitting on a chair with the hips and knees flexed at 90^{o} and the forearm at horizontal level.

Table 12. The Zancolli classification (Zancolli et al. 1983)

Type I	Complete extension of the fingers with the wrist in the neutral position or with less than 20 degrees of flexion
Type IIa	Active extension of the wrist with the fingers flexed
Type IIb	No active extension of the wrist even with the fingers flexed
Type III	No active extension of the fingers even with maximum wrist flexion

8.3.5 King's hypertonicity scale (III)

This scale was used for the assessment of manual dexterity. Copley et Kuipers (1999) developed a clinical reasoning protocol to assess upper limb hypertonicity which included the King' hypertonicity scale with alternating movements. This test is generally recommended for more definitive measurement of hypertonicity in occupational therapy (King 1987). The grading of King's scale is shown in **Table 13**.

Table 13. King's hypertonicity scale (King 1987)

1. Unable to perform the function
2. Manages to perform the function only with assistance
3. Manages to perform the function only partly
4. Manages to perform the function with some difficulty
5. Normal function

The following functions were tested:
- How to open a screw top
- How to thread beads on a string
- How to use the affected hand when throwing a ball (diameter 20 cm)

Throwing a ball with two hands was assessed slightly differently:
1. No active touch with the hand
2. Touches the dorsum of the hand
3. Touches the radial part of the hand
4. Touches the whole palmar hand
5. Normal function

8.3.6 Timing of clinical assessment

Rhizotomy study: In the first study (I), all the children were assessted by one or two paediatric neurologists (Hm, TS, LvW), together with a physiotherapist (RJ). The children who were allocated to the SPR +PT group were also examined by one operating surgeon (GB, JM) and a neurophysiologist (KS) before the operation. The follow-up examinations were conducted jointly by one of the paediatric neurologists and the physiotherapist at six months, 12 months, three years and five years postoperatively. The children in the PT group (N=21) were normally examined every six months by one of the three paediatric neurologists, but some of them were also examined by a paediatric neurologist at their own regional hospital. The follow-up data for these children were obtained.

ES of the lower limb: The first 17 children who fulfilled the criteria for Study II and were seen during a six-month period (November 1998 to April 1999) were recruited to this study. Informed consent was obtained from their parents. The children were assessed before and after the ES period and the assessments were repeated one, two and nine months later. All the assessments were carried out by the same persons (HM, RJ).

ES of the upper limb: All 12 children in Study III were assessed clinically approximately four weeks before and at the beginning of the electrical stimulation period and at the end of the ES period and three months later. On all occasions, the assessment consisted of a GAS, the Zancolli classification and muscle testing according to Daniels and Worthingham (supination in arm extension and arm flexion) and were carried out by the same persons (HM and RJ). In addition, manual dexterity was tested so that the author, occupational therapist AT, performed and videofilmed testing with the modified King's scale immediately before and three months after the cessation of the treatment period. These tests were later rated by an external, independent occupational therapist, who was blinded to the clinical case histories and did not know which test occasion she was assessing.

MENS: Study IV consisted of a baseline period lasting a minimum of four weeks, followed by four weeks of treatment with microcurrent stimulation. The subjects were assessed one month before, immediately before the treatment period and immediately after it.

8.4 Interventions

8.4.1 SPR (I)

In our series, the approach followed the general principles outlined by Peacock et al. (1987) Laminotomy was performed so that the re-fixation of the laminae was possible at the end of the operation. The operation was started at the level of S1. The root was revealed and the posterior part was identified through its dorsal position **(Figure 5)**. In the event of identification problems, re-assurance was sought with the stimulus threshold. Subsequently, the posterior roots were divided into six rootlets and the proportion of the rootlets (be it one third, a half of a third) to be cut was decided in advance. When spasticity (according to the clinical assessment) was more pronounced in the muscles innervated by the lumbar plexus, the weight of the operation was shifted upwards and, when spasticity was higher in the muscles innervated by the sacral plexus, more rootlets were cut downwards. A device was developed which enabled us to lay six rootlets side by side and stimulate them one by one. The rootlets with the most pathological EMG responses were cut, without outnumbering the maximum number of rootlets decided in advance. In the SPR study (I) of the

children undergoing surgery, there were no drop outs during the first three years after operation, but two children dropped out during the five-year post-operative assessment. Among the control children, one child was lost to follow-up by the third year and a total of two children had been lost by the last five-year follow-up. During the follow-up, spasticity was only measured in the group undergoing surgery

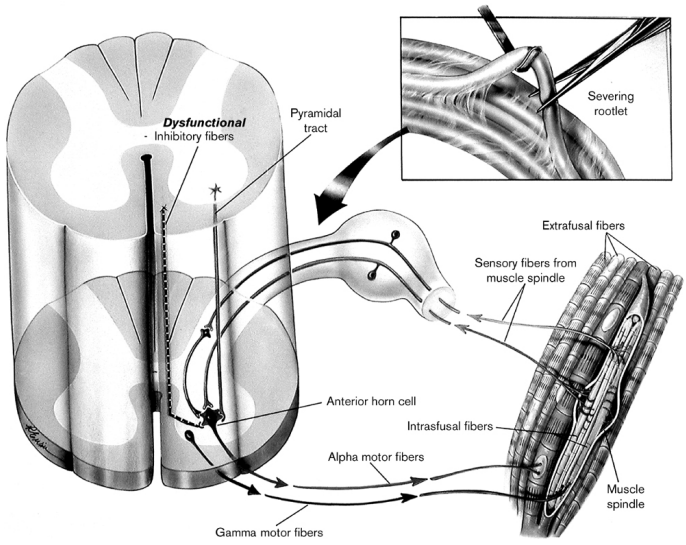


Figure 5. Depiction of spinal cord indicating location of dorsal rootlets transaction

8.4.1.1 Neurophysiological stimulation

Bipolar constant current stimulation was used. Individual roots were first stimulated with single stimuli in order to find the threshold level. This helped to differentiate between the anterior motor root and the posterior sensory root, as the threshold level of anterior roots is much lower. A one-second, 50Hz train of stimuli was given in order to find the primary function of the root. After dividing the roots into six rootlets, every rootlet was given the same train of stimuli separately. At the end, the remaining non-operated roots between L2 and S1 were stimulated together.

Eight channels representing four muscles bilaterally were recorded with bipolar needles. The recorded muscles depended on the examined root. Responses were judged as normal when they were restricted to the correct side and root level, the amplitude was attenuated and the duration of the response was no longer than the stimulation. On the other hand, responses were regarded as pathological if they spread to the opposite side or inappropriate levels of the roots, if they lasted longer than the stimulation or if the amplitude during stimulation was increased.

8.4.2 Treatment with sensory-level ES (II, III)

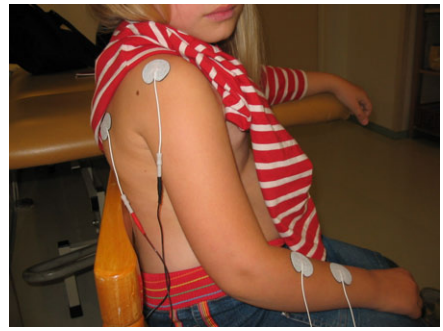
An ENS 931 EMPI unit was used as the neuromuscular electrical stimulator. This equipment produces symmetrical biphasic waveforms. At the beginning of the therapy, stimulation was given at a frequency of 10-20 Hz, which produced a tickling sensation and sensory input but no muscle contraction and no pain. The goal of ES was to increase sensory awareness and muscle response. The current required to achieve this varied from child to child (variation of 4 to 20 mA). The pulse

duration was fixed at 300 µsec (set by device). On:off times were set at one second on followed by one second off. If the sensation started to vanish, the intensity was increased.

The regular, basic therapy in these children was physiotherapy and occupational therapy based on NDT principles. Originally, the duration and frequency of physical therapy and occupational therapy were set according to individual needs and were not changed during the entire study. During the treatment period, the children received ES at sensory level as an add-on therapy during their therapy sessions, which were otherwise conducted as before. The lower limb stimulation study (II) consisted of a treatment period (one month, tibialis ant muscle stimulation) during the PT sessions (one to three times a week) and the follow-up periods (two months and nine months) **Picture 2**. The upper limb study (III) (wrist dorsiflexors and infraspinatus) consisted of a baseline period (four weeks), treatment period during PT and occupational therapy sessions (five weeks) and follow-up (12 weeks). During the treatment period Study III, the children had a total of twelve ES sessions **(Picture 3)**.

Picture 2.

Picture 3.



8.4.3 Treatment with MENS (IV)

Micro100 Dual channel equipment was used. The treatment parameters were 300 µA constant slope wave current with 30 Hz. Adhesive gel electrodes from both channels were used so that the positive electrodes were placed on the belly of the gastrocnemius muscle and the negative electrodes on both sides of the Achilles tendon. A total of 10 children received ES three times a week, whereas two children in the older group had this therapy twice a week. The parents treated their children at home with MENS for one month, with the subjects receiving at least five hourly treatments a week (Public. IV, Figure 1, page 671).

The MENS study (IV) consisted of a baseline period lasting a minimum of four weeks, followed by four weeks of treatment with microcurrent stimulation.

8.5 Statistical analyses

In the statistical analyses, non-parametric analysis of variance was used primarily to assess the significance of the change. The alpha level was set at 0.05. The analyses in the study (II) were calculated using the number of feet treated (23 stimulated feet) because there were children with either diplegia or hemiplegia.

When applicable one-way ANOVA analysis was used primarily to assess the significance of the changes, for the multiple comparisons and Tukey-Kramer was used as a post-hoc test.

9. RESULTS

9.1 SPR

The SPR + PT children (n=21) and the PT control children (n=21) did not differ significantly from one another with respect to age, gender, lower limb spasticity or the mean functional scales prior to the start of the study. In the children undergoing surgery, 22-60% (mean 44.8%) of the rootlets at the level of spinal vertebrae L2-S1 was cut.

Change of function

The change of function scores over time are shown in **Table 2** of the publication I.

GMFCS: At the baseline evaluation, the groups displayed equal functional skills. Both groups had mean scores at the same level and all the changes were insignificant throughout the follow-up period (Public. I, Table 2, page 69).

Illinois-St.Louis Scale: During the first year, both groups demonstrated a small functional improvement with a mean score of 1.30-1.50. All these changes and differences were insignificant. At the three-year assessment, the comparative children with normal intensity PT had better functional skills than the group undergoing surgery. At the five-year-follow-up both groups had significantly better mean function scores than at the first assessment, but there was no significant difference between the groups (Public. I, Table 2, page 69).

Change in spasticity

There was a significant loss of spasticity after SPR at all the post-operative assessments until three years postoperatively. Re-spasticity appeared slowly, but a significant increase in muscle tone was only noted in the hip adductors five years postoperatively compared with the one-year follow-up. The number of rootlets cut was associated with the change in spasticity (Public. I, Table 3, page 69).

9.2 Sensory level ES of lower extremity

The results of GAS immediately, two and 6-12 months after the stimulation period:

Immediately after the stimulation period, the GAS showed good progress (score 1 or 2) in 15 out of 17 children (21 feet of 23). In all, 12 children (14 feet) scored GAS 2 and five children (seven feet) scored GAS 1. The two failures (score 0) were two children with spastic diplegia, where only one foot changed The GAS showed a further slight improvement two months later compared with baseline as 16 of 17 children (22 feet of 23) scored 1 or 2. Of these, 13 children (15 feet) scored 2 and four children (seven feet) scored 1. There was one child with spastic hemiplegia, who deteriorated to baseline level. As compared to baseline, the improvement in the GAS score after 6-12 months still remained, as 16 of 17 children (21 feet out of 23) scored 1 or 2. Within this group, eight children (10 feet) scored 2 and eight children (11 feet) scored 1. One child with spastic diplegia lost the skills she had had at two months and returned to her baseline functional level (Public. II, Table 3, page 42)**.**

The results of the mean active dorsiflexion (ROM) with flexed and extended knee are presented in Table 14. The mean ROM increased significantly and remained significantly increased during the whole follow-up period. Standing on one foot improved significantly immediately after

the stimulation period and stayed so through the nine months period (Table 14). Hopping on one foot improved immediately after the stimulation period but not significantly. However, during the two and nine months follow-up it became statistically significant. The details of the results are given in the publication number II (Public. II, Table 4, page 42).

Table 14. Effects of sensory level ES in active dorsiflexion and one-foot activities in 17 children with CP (23 stimulated legs)

	Before intervention	After intervention (months)		
		0	2	9
Dorsiflexion, knee flexed (degrees)	7.9	16.0	17.1	15.0
Dorsiflexion, knee extended (degrees)	1.7	9.7	11.6	10.2
Standing on one foot (sec)	3.0	6.4	8.6	5.85
Hopping on one foot (times)	1.7	3.4	7.7	5.85

9.3 Sensory level ES of the upper extremity

All the children co-operated well during the programme. During the baseline period, there was no change in the function of the upper extremity.

The results of the effects on ES on upper extremity in supination in 12 hemiplegic children immediately after and three months after the cessation of stimulation are shown in Table 15. When the arm was flexed the result of supination was better in older group immediately after the stimulation period. When the arm was extended children in the younger group had better results. The more detailed results are in the publication number III (Public. III, Table 4 and Table 5, page 87; Table 6, page 88).

Table 15. Effects of sensory level ES in upper extremity in 12 children with CP (Daniels and Worthingham, 1972)

	Before ES		After ES	
	One month	0 month	0 month	3 months
Supination with arm flexed :				
All	2.0 (1.80-2.53)	2.0 (1.80-2.54)	3.0 (2.58-3.58)***	3.0 (2.86-3.65)¤¤¤
Children < 4 years	2.0 (1.37-2.96)	2.0 (1.38-2.95)	3.0 (2.34-3.67)*	3.5 (2.48-4.19)
Children 4 years or >	2.0 (1.74-2.59)	2.0 (1.73-2.60)	3.5 (2.14-4.20)**	3.0 (2.73-3.60)¤
Supination with arm extended:				
All	2.0 (1.35-2.14)	2.0 (1.36-2.15)	2.5 (2.17-2.83)***	3.0 (2.25-3.08)¤¤¤
Children <4 year	2.0 (0.62-2.38)	2.0 (0.62-2.38)	3.0 (2.12-3.21)**	3.0 (2.04-3.62)¤
Children 4 years or >	2.0 (2.00-2.00)	2.0 (2.00-2.00)	2.0 (1.79-2.88)	2.5 (1.93-3.08)

Statistical significance of change:
Comparison of assessment pre vs post 0 month *=p<0.05, **=p<0.01, ***=p<0.001
Comparison of assessment pre vs post 3 months : ¤=p<0.05, ¤¤¤=p<0.01, ¤¤¤¤=p<0.001

9.4. MENS

During the baseline period, no significant changes occurred. Compared with the baseline recordings, the passive ROM of ankle dorsiflexion with the knee flexed ($p < 0.001$) and extended ($p<0.001$) increased to a statistically significant degree after the MENS treatment period (Public. IV, Table 1, page 672).

Similar significant changes were noticed for the angles of maximum popliteal ($p<0.001$) and ankle dorsiflexion ($p=0.0012$) in the standing position with maximum flexion of the knees with the heels in contact with the floor. In addition, the ROM of active dorsiflexion of the ankle with the knee flexed ($p<0.05$) changed significantly, whereas the ROM of active dorsiflexion of the ankle with the knee extended did not. The ability to stand on one foot improved to a statistically significant degree ($p<0.05$), but hopping on one foot did not (Public. IV, Figure 3, page 673).

10. DISCUSSION

10.1 Main results

Children in the groups of selected posterior rhizotomy and intensive physiotherapy experienced steady development during the five-year follow-up period and no statistically significant differences were observed in the mean functional scores between the groups. Although we failed to demonstrate any additional effect of SPR on the motor development of children with spastic CP, SPR appears to contribute to the resumption of motor development in children with arrested motor development.

Following the use of electrostimulation at sensory level during a five-week period, the children with CP developed new active selective muscular movements and stability in their lower extremity (dorsiflexion, inversion-eversion and toe flexion-extension). Moreover, hand function improved in both age groups at sensory level. ES of the upper extremity in conjunction with physiotherapy enabled the children to find and master the desired movement. Perhaps the most important observation was the fact that the new skills did not vanish during the follow-up. This speaks in favour of the fact that motor learning occurred.

In our MENS study, it was seen that the relief of ankle contracture using microcurrent therapy on the gastrosoleus muscle group can produce 10-15 additional degrees of passive ROM.

10.2 General design

10.2.1 SPR (Study I)

This study emerged from a study which was originally planned as a joint Nordic multicentre controlled study. However, it turned out to be impossible to recruit any controls. For ethical reasons, all the candidates for surgery were offered the operation or traditional PT, but no families agreed to adopt the PT only alternative. Similar problems have apparently also been encountered elsewhere, as the number of SPR studies of this question is still low. We think that our approach of comparing two similar, but not identical groups yielded clinically highly relevant information. However, we acknowledge, that the study design does not represent a true case-control design.

10.2.2 Electrostimulation (Study II, III, IV)

There is no other published study where ES at sensory level has only been used as an add-on therapy or MENS therapy has been used in children with CP. In the case of the ES studies (II, III, IV), the main weakness was the lack of controls. The studies were planned as open pilot studies. In order to overcome the drawbacks of not adopting a case-controlled design, we chose to have a minimum baseline period of one month before the stimulation or the follow-up period was repeated three times. It must, however, be admitted that the use of a control group would have added reliability to the analysis. However, despite the fact that the Department of Child Neurology at Helsinki University Central Hospital serves a quarter of the whole of Finland, it was not possible to identify enough comparable patients to form a control group. Therefore, the effect of ES should be studied by means of multicentered study.

10.2.3 Series

Our SPR (I) series consisted of 42 children with CP (21 operated plus PT and 21 PT only). Compared with the three randomised, controlled studies with a similar study design, the series are of a similar size or smaller (Steinbok et al. 1997a: 28 children, McLaughlin et al. 1998: 38 children, Wright et al. 1998: 24 children). Our inclusion criteria for SPR were different from those in previous studies, because we only included the children who had a standstill of at least six months in their motor development and had therefore dropped from their motor developmental curve. The

obvious limitation of our design is that it was not truly a case-control study and the results therefore need to be evaluated with caution (Steinbok et al. 1997a, McLaughlin et al. 1998, Wright et al. 1998.

According to NMES (II&III) studies in the literature there are a many case studies but there are only three randomised studies in which the series sizes are between 20 and 26 children. The lack of a control group in our study means that no adjustment for maturation-induced possible spontaneous development could be made. It is unlikely that an improvement in new active movement in lower or upper extremity function like that shown in our studies would have taken place irrespective of the intervention and spontaneously, as no such changes were observed during the initial baseline period.

In our first ES study (II), 23 legs were stimulated and the follow-up periods were two and nine months. In the second ES study (III) there were a total of 12 children. In this study, we had two groups: Group A= under four years of age and group B= four years of age and older and we compared the results with one another. Finding adequate controls in therapeutic studies of children with CP is a well-known problem, which is reflected by the scarcity of case-control studies in this group of children.

There are no other MENS studies of children in the literature and only one randomised comparative study has been performed in adults of microcurrent treatment for Achilles tendinopathy. In our MENS study (IV), we started with a pilot study with those hemiplegic children with severe equinus who had undergone Achilles-surgery twice without a positive response. After obtaining positive results, we enlarged the group to 12 children with persistent equinus.

10.2.4 Rhizotomy technique

A modification, in which the procedure is performed through a laminotomy at L2-L5, was introduced by Peacock et al. (Peacock and Staudt 1990) and is widely accepted. In our series, the approach followed the general principles outlined by Peacock et al. The operation was started at the level of S1. The majority of neurosurgeons believe the preservation of S2 roots during surgical procedures may be important for sexual function and may also contribute to a reduction in postoperative bladder disturbances (Kim et al. 2002). In our method, 22-60% of the rootlets between L2-S1 were cut (mean 44.8%),

10.2.5 Administration of ES

A discussion of ES requires a definition of the terms that are frequently used to differentiate the types of stimulation. When we used NMES at sensory level as an add-on therapy, the primary goal was to improve awareness of the affected body part and thereby function, because a tactile model of body surface is an integral part of body scheme which is needed for motor planning and execution (Haggard 2005). In this respect, our studies differ from most other studies of ES in children with CP, as their main goal has been to improve muscle contraction (Carmick 1993a,b, 1995, 1997, Scheker et al. 1999, Wright and Granat 2000, Park et al. 2001). NMES is the electrostimulation of the muscle through the motor nerve, usually with the goal of improving strength (Carmick 1993a,b, 1995, Park 2001), improving range of motion (Hazlewood et al. 1994, Comeaux et al. 1997) or facilitating motor learning (Carmick 1993a,b, 1995, Pape 1993). The underlying assumption has been that the sequential function of the muscles of the child can be improved by firing the agonist muscles by means of ES. Firing the agonist polysynaptically inhibits the antagonist or spastic muscle in the reflex arc, thereby reducing the co-contraction CP (Scheker et al. 1999, Wright and Granat 2000, Reed 1997).

10.2.5.1 Treatment parameters

The treatment parameters employed by different authors in the text in Table 5b vary from one author to the other. The pulse duration used in our study and in most of the other NMES studies was

300 µsec and this might be constant depending on the machines. There are studies by Hazlewood et al. in 1994 and van der Linden et al. in 2003 which used a pulse-duration of 100 µsec. In the first of these studies, positive results in passive ROM were obtained, whereas, in the study by van der Linden et al., no significant improvement was obtained in measurements of muscle strength, gait analysis or passive ROM in the eight week stimulation group (gluteus maximus) when compared with the control group.

Frequencies were generally in the range of 30 Hz to 45 Hz. In some studies including ours lower frequencies (5 to 7) were initially used, but, when the child was used to the stimulation, the level was raised to 30 to 45 Hz (Carmick 1993a,b, Carmick 1995, van der Linden et al. 2003). Depending on the different studies, there was variation in the activation on:off times. The on:off times in the TES studies were generally equal (Pape 1997, Sommerfelt et al. 2001, Dali et al. 2002), but in other studies some authors used equal times (Carmick 1993a, b, 1995, Wright and Granat 2000) and others ensured that the "on" time was half the "off" time (Hazlewood et al. 1994, van der Linden et al. 2003). We chose the parameters that were used in studies by Carmick (1993 a,b, 1995). The on:off time that is usually used in NMES (Carmick 1993a,b, Hazlewood et al. 1994, Comeaux et al. 1997) has been reported to vary from 4s-15s/12-20 s. In our study, we chose the shorter on:off ratio (both one second), because the children found it comfortable and easy to identify.

The main difference between our approach and that used in the other studies is that we used a symmetrical wave form compared with the others who used asymmetrical wave forms. The reason for this was that the machines we used produced only symmetrical wave forms.

Carmick documented the effects of task-oriented NMES (both upper and lower limbs) with a series of children of different ages and types of CP. When used at muscle contraction level, NMES was most commonly applied for 15 to 20 minutes a week in a task-oriented therapy setting (Carmick 1993a,b, 1995) or for up to one hour daily for 35 to 60 days when applied at home (Hazlewood et al. 1994, van der Linden et al. 2003). In the latter way and in TES studies, the stimulation was given without task-specific therapy.

One reason for using a short treatment period (30-60 min) in our studies was the idea that electrical stimulation may cause sensory fatigue. Previously it had been shown that even ten minutes' stimulation can cause muscular fatigue when using stimulation at contraction level (Baker et al. 2000).

In comparison with the TES used by Pape et al. (1997), it should be noted that, in our study the stimulation level was similar, but the duration was short (30-60 min) compared with TES (7-8 hrs) (Pape 1997).

Another reason for choosing the present therapy protocol (4-6 weeks) was that this duration appeared to be easily tolerated by the children and their families. Because this treatment was planned as an add-on therapy, it was considered to be an advantage to have the stimulation simultaneously with the physical therapy. The duration of electrotherapy treatment periods varies from a four- to five-week regimen to 20 months (Carmick 1993a,b, 1997b). The results of all these somewhat divergent treatment protocols appear to be at least comparable, which may indicate that the results are not linearly related to the duration of the input. Short, clearly goal-oriented treatment periods are more readily accepted by the families. The present study therefore offers support for the use of ES for limited periods only in the course of the entire rehabilitation programme. The optimal indications, timing and duration of add-on electrotherapy are still unclear and need to be addressed in more extensive follow-up studies.

10.2.5.2 MENS

The four-week stimulation period was chosen, as previous clinical experience has shown that a time period of this duration is easily tolerated by the children and their families. As the basic aim

of this pilot study was to determine whether MENS had any measurable effects, we confined the assessment to very basic areas. Because of the design of the study and the limited battery of assessments, conclusions need to be drawn cautiously and more extensive studies are needed to demonstrate the functional value of the present therapy.

10.2.6 Evaluation tools

Quantitative assessments are most frequently used in SPR studies like ours together with the Ashworth scale or some variation of this scale (Steinbok 2001). In the review of outcomes after selective posterior rhizotomy for spastic cerebral palsy by Steinbok (2001), there is a very strong evidence of the benefits of SPR in reducing spasticity. These results include the randomised controlled trials, each of which showed a significant reduction in spasticity after SPR and PT compared with a control group of patients who only received PT. These quantitative assessments have been generally performed up to two years after SPR, with only one study examining the outcome at five years (Gul et al. 1999, Steinbok 2001). GAS is generally accepted and used in situations in which special goals are needed. One advantage of the GAS is that the set goals can be individual or general. The scale also worked well in our studies.

In the rhizotomy study, GMFM was only used for half the children who participated in the study. This explains why we did not include it in the final results. Motor function was measured using two different methods, the Illinois-St Louis Scale and GMFCS. As an evaluation tool, a gait laboratory would be ideal while measuring gait pattern. When we started our study, the gait laboratory services were not available.

One potential source of inaccuracy is the set of assessment tools chosen for hand function, which is a complex behaviour and not easily evaluated. One instrument is not enough. Traditional hand function tests in children mainly use two perspectives (Eliasson 2004). The first is an evaluation of basic motor components such as strength, speed or dexterity. The results of these tests tell us something about the impairment, but they do not give us information about or predictions of the ability to perform activities. The second perspective is an evaluation of ability, often age norm referenced, to perform skilled tasks such as drawing, cutting with scissors, displacing objects of different sizes and weights or stringing beads. However, children with cerebral palsy may or may not follow the normal development. There is hardly any assessment which provides information about a child's ability to use the affected hand in everyday activities after unilateral impairment. Although some test items involve the use of both hands, no test is targeted at people with one well-functioning and one affected hand. The most difficult group to study are the children with hemiplegic CP under the age of five, because there is no standardised test. When the children are five or older, there is standardised Melbourne test. In order to avoid using different tools for the same functions in different age groups, we decided to use the methods that could be used for the entire group. We were therefore unable to use the Melbourne Upper Extremity Assessment (Bourke-Taylor 1997) or the Purdue Pegboard Test (Hurvitz et al. 2003) which would have been optimal choices but can be used only from the age of five years. Orthopaedic specialists have used the Zancolli classification to evaluate the results of hand surgery. Scheker et al. (1999) used the Zancolli classification successfully for children with CP and managed to demonstrate improvements after using hand orthoses and electrostimulation together.

10.3 Results

10.3.1 SPR

10.3.1.1 Spasticity

In earlier studies (Steinbok et al. 1997a, McLaughlin et al. 1998, Mittal et al. 2002), the results demonstrated that lower-limb spasticity was significantly reduced at one year postoperatively and this beneficial effect was maintained three and five years postoperatively. In our present study, on the other hand, there was a significant loss of spasticity after SPR at all the post-operative assessments until three years postoperatively. Re-spasticity appeared slowly, but a significant increase in muscle tone was only noted in the hip adductors five years postoperatively compared with the one-year follow-up. The number of rootlets that were cut was associated with the change in spasticity. During the follow-up, spasticity in our study was only measured in the group undergoing surgery.

We did not use the passive range of motion for evaluation. In our study, as in the study by Kim et al. in 2001 the majority of patients suffered postoperative hypotonia lasting a few months after the operation, but they were able to overcome this by scheduled intensive PT.

10.3.1.2 Function

In the dimension of functional limitations, the results of ambulation, various non-validated motor function scales have been used in two control (McLaughlin 1998, Steinbok 1997a) and one comparative (Marty et al. 1995) studies. On the Illinois-St Louis Scale during the first year, both groups demonstrated a small functional improvement with a mean score of 1.30-1.50. All these changes were insignificant. At the three-year assessment, the comparative children with normal intensity PT had better functional skills than the group undergoing surgery. After three years of follow-up six children out of 22 showed progress by one or two levels on the Illinois-St Louis scale and also maintained this result at five years from surgery. The corresponding figures in the PT only group were 10/22 at three years and 5/22 at five years.

At the five-year follow-up, both groups had significantly better mean function scores than at the first assessment, but there was no significant difference between the groups. In McLaughlin's study eight of 21 improved their ambulatory level after SPR at the two-year follow-up, but this was not statistically different from controls (McLaughlin et al. 1998). In the study by Steinbok, the ambulation level increased in five of 10 (50%) of those who were able to improve after SPR, but there were no improvements in the control group at the nine-month follow-up (Steinbok et al. 1997a). In the study by Marty et al., the results for 50 diplegic children undergoing SPR operations were compared with 50 diplegic children undergoing orthopaedic procedures. Fifty per cent of those with scope for improvement improved their ambulatory level and, after soft-tissue release, this figure increased to 58% after one to six years of follow-up (mean 4 years) (Marty et al. 1995).

There are three controlled studies (91 diplegic children in all), where the Gross Motor Function Measurement (GMFM) has been used. In these the outcome of SPR as expressed by GMFM ranged from 3.2% to 12.1% in different studies. In the two studies with a follow-up period of nine to12 months, the improvement in mean GMFM was significantly greater in the SPR group than in the comparison groups, but there was no difference in one control study with a two-year follow-up (Steinbok 2001). In our study, the GMFCS was also used it compares functional skills with age. Both our study groups had mean scores on the same level throughout the follow-up period. There were no children who changed classification level during the five-year follow-up in the operated group, but three children in the PT only group in which there were a total of 22 children recorded results that were one classification level higher. It is, however, important to remember that the motor development had arrested in the children in the SPR group during the last six months before the operation. There is another study by Engsberg et al. from 2002, in which the same classification was used, but the follow-up was only eight months (Engsberg et al. 2002).

SPR is usually advised before children develop many fixed deformities (Peacock and Staudt 1990, 1991). The majority will still require corrective orthopaedic surgery after SPR and some deformities may increase after rhizotomy (Greene et al. 1991). In the study by Carrol et al. (1998), in which 131 CP patients underwent SPR from 1986-1994, 112 of them had adequate follow-up. No statistically significant change in ambulatory status was found. A total of 71 (65%) patients required orthopaedic intervention for continued contracture and deformity (Carroll et al. 1998). In our SPR group, seven of 21 children also required orthopaedic operations during the follow-up period compared with five of 21 in the PT only group.

Our follow-up appears, however, to show that this method is still an alternative for patients with arrested motor development, despite optimal conservative therapy, or for those who require relief from spasticity with painful muscle cramps or for other very special reasons. The last rhizotomy operation took place in 1998 in Helsinki.

10.3.1.3 Complications

In the retrospective study by Steinbok and Schrag (1998) with 158 children who had undergone SPR, the short-term complications of SPR are infection, incontinence, sensory changes and excessive weakness. The only complications in our study were transient pain (n=4) and incontinence (n=1) lasting no longer than two weeks. Concerns regarding this SPR procedure have related to its long-term effect on function, the potential production of weakness, the possible development of spinal deformity and the continuing need for orthopaedic intervention,

Long-term complications like spondylolisthesis and spondylolysis have been mentioned (Peter and Arens 1993), as well as lumbar lordosis (Houle et al. 1998). Using our technique, laminotomy was performed so that the re-fixation of the laminae was possible at the end of the operation. This could be the reason why we did not encounter any spinal problems.

10.3.2 Electrostimulation

10.3.2.1 Lower extremity

The overall aim of this study was to determine whether sensory level ES to the tibialis anterior muscle as an add-on therapy during PT sessions facilitated voluntary movement in order to see whether ankle dorsiflexion could thereby be improved and we therefore confined our assessments with ROM and GAS. Usually only passive ROM has been assessed, but, as active ROM is functionally more important, we also measured key active ROM. In our study the children improved their active dorsiflexion with knee flexed and knee extended approximately 10 degrees. Perhaps the most important observation was that all the children acquired new, active muscular movements (inversion-eversion and toe flexion-extension). This may explain the fact that the time the children were able to stand on one foot was twice as long as before the intervention. In line with this hopping on one foot improved three times. The fact that the new skills did not vanish during the follow-up speaks in favour of the fact that motor learning occurred (Giuliano and Poirier 1991, Carmick 1995). From a functional point of view, it is important that the original supporting dynamic orthoses of 10 children could be replaced by less supporting ones, such as foot orthoses, during the follow-up period of nine months. Some of the parents of the children with hemiplegia reported that their children did not need any support when cycling. When the results were analysed so that the children were split into two groups, under seven or over seven years of age, it was found that age analysed in this way did not influence the outcome.

A different approach is represented by Carmick's case report (1995), in which she used NMES to strenghten the spastic gastrocnemius in a child with spastic diplegia and reported a positive result (Carmick 1995). Her comment was that her major goal was not strengthening but function. It seems that there must be an adequate amount of strength in order to have the function

(Carmick 2004, personal comment). Similarly, Comeaux et al. (1997) demonstrated an improvement in both ROM and gait patterns after NMES applied to the gastrocnemius or gastrocnemius/tibialis anterior (Comeaux et al. 1997). In both studies, the favourable results were attributed to reciprocal inhibition. Stimulating the tibialis anterior inhibits the gastrocnemius and stimulating the gastrocnemius inhibits the tibialis anterior so that the co-activation of the two muscles is diminished. In addition, NMES provides a proprioceptive input and acts as a type of biofeedback device (Baker et al. 2000, Carmick 1995). The potential advantage of sensory level ES is that it can enhance the sensory input, thereby increasing the child's awareness of muscular function. In our study, the positive effect of ES was not mediated through activation of the muscle fibres, but through activation of cutaneous and muscle afferent pathways which modulate excitability levels of interneurons and alpha motor neurons (Rose and McGill 1998, Carmick 1995, Baker et al. 2000).

There are few authors (Rosenbaum 2003, Sussman and Aiona 2004, Goldstein 2004) who critically review electrostimulation for the treatment of CP. It is clear that there are no qualitatively and statistically highly satisfactory studies of ES and CP in the literature. Most of the studies in this area come from experience of the rehabilitation of adults. ES can be used for rehabilitation in many different ways. Because of the nomenclature difficulties in the field of NMES, many authors who are not acquainted with ES and its use among children with CP very often just mean TES studies when talking about ES (Rosenbaum 2003, Goldstein 2004). In a number of studies using TES, the stimulation was used at sensory or subsensory level and was applied overnight during sleep (Pape et al. 1993, Sommerfelt et al. 2001, Dali et al. 2002). The reported results have been very contradictory, perhaps reflecting subtle, yet important, differences in the protocols. Children with early acquired motor deficits often have difficulty producing selective movements in an affected extremity and it has been suggested that this is due to a form of developmental apraxia caused by defective motor planning in early infancy (Beck 1997, Brown et al. 2000). Daytime stimulation aims to provide feedback to the brain about the muscles that are activated during therapy. Stimulation at sensory level helps the child to"localise" the muscle he/she is trying to use. The feedback information from the child's own movements facilitates motor learning (Pape et al. 1993, Larin 1997, Reed 1997). The physiological activation order for motor units has been said to be the opposite of electrical stimulation (Gersh 1994, Baker et al. 2000). However, in the recent study by Gregory and Bickel (2005), the authors say that the majority of the evidence suggests that EMG-induced motor unit recruitment is non-selective and that muscle fibres are recruited without obvious sequencing related to fibre types (Gregory and Bickel 2005). According to Pape's protocol, TES must be used first, followed by NMES to obtain muscle strength and function (Pape et al. 1993, 1997). This design contributed markedly to the variability of the treatment intensity. Another factor with a similar effect was the fact that the intensity of PT tends to be higher in spastic diplegia than in hemiplegia. The evident drawback of this design is the relatively low or individually very variable frequency of stimulation sessions, but the aim of the study was not to change the children's basic PT programme.

10.3.2.2 Upper extremity

Carmick's way (1993a,b) of using therapeutic ES differed from ours, as she started to stimulate at sensory level in order to get the child used to it and then increased the intensity to achieve muscle contraction. We used the ES at sensory level throughout the study to help to "localise" muscle use by giving tactile and proprioceptive information from periphery to central. In the study by Dewald et al (1996), adult subjects with hemiplegia were studied. The stimulation was performed over the area of the biceps muscle at an intensity level well below the motor threshold but just above the sensory threshold. They used a frequency of 20 Hz with a 0.1 millisecond pulse

for a period of 10 minutes. This short exposure produced a measurable reduction in spasticity for at least 30 minutes following ES.

Although these studies did not focus on the role of sensory awareness in motor control, they suggest that sensory stimulation in children with CP in conjunction with PT may improve motor skills. Our results can also be compared with those obtained by Scheker et al. (1999) who, in an observational study of 19 patients, demonstrated a marked improvement in upper–extremity function using simultaneous dynamic bracing and NMES for 15 months in children with CP. The Zancolli classification revealed that all the children moved up one to three grades. Fourteen children moved up two grades and three children moved up three grades (Scheker et al. 1999). One drawback of the study by Scheker and co-workers was that it was not possible to judge whether the effects were due to ES, dynamic bracing or both. Our study appears to indicate that simultaneous bracing may not be crucial. Wright and Granat (2000) treated eight children with CP for six weeks with functional ES for wrist extensor muscles, and demonstrated that hand function improved compared with baseline readings. They speculated that functional ES increased the strength of the wrist extensors and the flexibility of the soft tissue surrounding the joint, thereby increasing active and passive ROM. In our study it was interesting to notice that after the stimulation period supination was better in the older group with the elbow flexed and supination was better in the younger group when elbow extended. The fact that the group of younger children in our study appeared to benefit more markedly may be explained on similar grounds; i.e. older children have shortened muscles which were less amenable to therapy.

The underlying pathophysiology of congenital brachial palsy is clearly different, but it is noteworthy that, in a study of children with congenital brachial palsy, conducted in 2000 by Brown et al., it was shown that there is not only a lack of movement but also a loss of sensory input from muscle, joint and skin receptors. The lack of visual feedback from the moving hand also impairs awareness of the limb (Brown et al. 2000). These theories could explain why, in our study, there was an improvement in ROM, accompanied by qualitative improvements (throwing a ball), in the children under four years of age. The fact that the results improved in the ball throwing test but not in screw-top test or in threading beads might be explained by the simpler motor function involved in ball throwing.

The favourable effect of our combination of sensory level treatment and motor activity can be explained at least in part by the results of studies by van der Weel et al. (1991). They demonstrated that children with hemiparetic CP achieved a significantly larger range of movement in the concrete task (explained by adequate proprioceptive information) than in the abstract task (van der Weel et al. 1991). There is the same kind of background in the studies of constraint-induced movement therapy for children with hemiplegia in which positive changes in function such as manual dexterity, sensory discrimination, and limb coordination have been reported (Charles and Gordon 2005).

10.3.2.3 MENS

Previous in vitro studies have demonstrated that the application of microcurrent can promote protein production (collagen) in fibroblasts and tenocytes, while in vivo studies using animal models have demonstrated that tendon and ligament tissue responds particularly well to this application (Cheng et al. 1982, Becker 1985, Gibson et al. 1998). In the first non-invasive study by Chapman-Jones and Hill (2002), it was shown that the application of microcurrent treatment has the potential to augment the healing process in chronic tendon pathology in human subjects (Chapman-Jones and Hill 2002). The encouraging results from our study can be partly explained by these previous studies, but to our knowledge this is the first study conducted in children with CP.

In a rat model, Akai et al. (1997) treated experimental contracture of the knee joint with implanted electrodes using MENS. The knee joint flexion angle after treatment at the intensity of 50 μA was 110 degrees, while it was 50 degrees in the control group. The rats which were treated with

the 20 µA intensity showed an improvement which was 10 degrees smaller. The authors speculated that the mechanical signals which are vital for normal tissue metabolism could be replaced by electrical signals, because they produce oscillatory forces and vibration in the tissue (Akai et al. 1997). In line with this, Gibson et al. (1988) demonstrated that ES produced an increase in the numbers of sarcomeres, thereby improving contractility (Gibson et al. 1988).

Direct current stimulation has the capacity to increase microcirculation in soft tissues (Bogie et al. 2000). Low-intensity DC therapy may increase blood flow in soft tissues by acting on vascular smooth-muscle mechanoreceptors and it is known that these structures respond to mild mechanical agitation causing vasodilatation (Jamney 1998). This may be related to the children's observation that their calf muscles were warmer after than before treatment. The blood circulation may have improved, making the warm muscle more flexible. The same thing could have happened in the Achilles tendons where the rise in tissue temperature produces no sensations but increases collagen flexibility. This observation should be viewed against the background information that, in a shortened muscle and tendon, protein synthesis is reduced relative to degradation and cross-sectional area and the mass of muscle is significantly reduced, while tendon stiffness is increased (Almeida-Silveira et al. 2000). When the shortened muscles and tendons are not treated adequately, there is a danger of developing myotendinous contracture. Not only is there tightness of muscles and connective tissue there are also effects on dorsal horn neurons. The results of experimental contractures in rats reveal that neurons which reacted to only normal motion signals before contracture changed their behaviour and responded as mechanical stimuli and were nociceptive (Ushida and Willis 2001).

Keeping a muscle in a shortened position is a disadvantage, as the number of sarcomeres in the muscle cells decrease and disuse causes atrophy (Shah et al. 2001). In these hypertonic muscles, these changes are accompanied by a change in the molecular mechanisms of muscle cells (Shah et al. 2001). During normal muscular rest, the myosin and actin overlap to some degree. These thick and thin filaments are able to slide over each other. This is achieved by the cross-bridges of the myosin attaching briefly to actin, while propelling the myosin along the actin in the presence of adenosine triphosphate (ATP) (Carey and Burghardt 1993).

In the spastic muscle, the mechanism for attaching and detaching is disturbed and the key dysfunction is a failure to disengage myosin and actin completely after activity. This is a central cause of abnormal thixotrophic properties of muscle (Bressel and McNair 2002). Thixotrophy has been defined as a physical change in the substance of the muscle after being mechanically agitated. In practice, this means that gel substances become less viscous (i.e. more fluid) with movement and gradually regain their gelatinous state with rest. Molecular bonds of substance are involved in this phenomenon, as the bonds are disrupted by movement and reformed when the movement forces cease. In the muscle, thixotrophic changes occur in the gel component of muscle (e.g. water and proteoglycans) and in the viscous resting myosin-actin cross-bridges (Whitehead et al. 2001). During immobilisation, the gel component of muscle becomes more viscous and produces increased resistance to stretching. This viscous resistance of a muscle decreases after exercise (Mayer 1997). It is not known whether resting myosin-actin cross-bridges contribute to viscous resistance in muscles other than spastic ones. Thixotrophy is also dependent on movement history, so that prior movement reduces stiffness, whereas prior stillness increases stiffness (Whitehead et al. 2001). Microcurrent stimulation produces mild pressure waves in the tissue and can thus influence the extracellular matrix of the cells. Because the matrix molecules are in contact with the cell membrane mechanosensitive receptors, the stimulation spreads through them to the cytoskeleton. Inside the cell, many enzymes and cell organelles including the nucleus are activated. As a result, there may be an increase in ATP production and the release of trophic factors influencing protein synthesis (Carson and Wei 2000). Interestingly, we also saw favourable effects in the children whose Achilles tendons had previously undergone surgery. Obviously, the microcurrent treatment changed the biomechanical and physiological properties of the collagen-deficient Achilles tendons.

Assumptions of this kind relating to the effect on collagen are supported by a study of tendon repair in an animal model by Nessler and Mass. In this study, microelectrically-stimulated tendons demonstrated a 91-per cent higher proline uptake than control tendons after seven days of stimulation, while hydroxyproline activity was increased by 255 per cent versus controls. The activity was also higher in the stimulated group 42 days after treatment. Histological sections revealed that intrinsic tenoblastic repair was enhanced by microamp stimulation (Nessler and Mass 1987). In another study, it was found that implanted electrodes delivering 10 to 20 μA of current speeded up the recovery of injured athletes suffering from ruptured ligaments and tendons. The use of MENS shortened the normal 18-month recovery period to only six months (Stanish 1984). Barry and Cheek (1994) showed that, in rabbits, immobilisation considerably worsened the alterations occurring in the morphological and physiological properties of the soleus following Achilles tendon section. Upon remobilisation, chronic low-frequency stimulation accelerated the recovery of both parameters. It has been suggested that cellular proliferation can be modified in two ways by direct current stimulation. If the proliferative rate is too low (as it is in immobilised tendons), it can be increased and, conversely, if the ratio is too high (as in muscle fibrosis), down-regulation occurs with a reduced proliferative rate (Vodovnik and Karbo 1992). It is possible that there was a change in the collagen metabolism of the gastrocnemius muscles similar to the changes noted by Lennox in the neck muscles of cancer patients (Lennox et al. 2002). As MENS can affect the function of cell nuclei, the treatment may have activated the genes that regulate collagen breakdown and induced the relief of fibrosis. In addition, the same mechanism offers an explanation for the improvement in balance, as collagen accumulation in the muscle is correlated with poor balance (Booth 2001). The children themselves liked the microcurrent treatment and afterwards mentioned that stretching the muscles did not hurt. This effect can most probably be explained by the fact that, when tissue tightness is reduced, fewer irritating mechanical stimuli are sent to the nociceptive system.

10.4 Neurophysiological basis for observed effects in Papers I-IV

Mechanisms for plasticity include the activity-dependent refinement of neuronal connection and synaptic plasticity as a substrate for learning and memory (Johansson et al. 2001a, Johnston 2003). We assume that the favourable effects shown by sensory-level ES can be explained as follows; giving electrostimulation at sensory level helps the children to localise stimulated muscles during the exercises (Das et al. 2001).

According to the neuronal group selection theory, after four months of age when the selection period is at its most intensive, great deal of “long-lasting” sensory information is required for selection (Hadders-Algra 2000b, 2001 ab, Forsberg 1999a). Park et al. (2001) showed in a control study that, in young infants with cerebral palsy (between 8-15 months), ES is effective in creating the awareness and stabilisation of the body when abdominal and back muscles were stimulated. Hadders-Algra et al. showed that training special muscles in infants at the age of five to six months can produce selected muscle co-ordination more quickly than in those without practice. If ES is given as an add-on therapy, it might make the whole process more effective.

In older children with borderline to moderate forms of CP, dysfunctions in the secondary variability are most prominent. Neuronal group selection theory suggests that children with these types of dysfunction will benefit from active practice, which will enhance the process of selection and thereby the production of better adapted motor behaviour (Hadders-Algra 2000b, Hadders-Algra 2001).

Sensory input linked to motor performance is now recognised as a critical factor in bringing about the desired motor improvement (Goldstein 2004). Active practice gives sensory feedback from limbs by activating spinal and supraspinal tracts and cortical areas which are needed to be activated for active voluntary movement. This in turn increases the activity of the children during

the therapy sessions and, when practising by themselves, the muscles are not over fatigued. This interpretation is, however, clearly speculative.

The neurophysiological approaches also have overemphasised the problem of spasticity and underemphasised other movement problems in children with upper motor neuron lesions (Ostrosky 1990). Spasticity cannot explain movement disordering and improved function may result in the reduction or elimination of spasticity (Gordon 1987). According to Dietz and Berger, muscle stiffness during locomotion in spastic hemiplegic patients is due to changes in the mechanical properties of muscle fibres (Dietz 2003, Berger et al. 1988).

Studies by Dietz and Harkema have shown that repetitive motor training provides sufficient stimulation of specific neural pathways to facilitate functional reorganisation within the spinal cord and improve motor output. Furthermore, appropriate sensory and especially proprioceptive input during training is of critical importance to achieve an optimal motor output from the spinal neuronal circuitry. SPR is an irreversible method which causes strong hypotonia immediately after rhizotomy operation and it then diminishes after six months. The reason for this could be the huge loss of proprioceptive information to CPGs (Dietz 2002, 2003, Dietz and Harkema 2004, Zehr and Duysens 2004).

Our finding that the effects of the ES treatment period did not disappear may support the hypothesis that the stimulation did not work at only local or spinal level. Support for such an assumption comes from studies of the effects of training using a mesh glove at subsensor level. They revealed that a signal increase took place in the primary and secondary motor and somatosensory areas, as demonstrated by functional magnetic resonance imaging or sensory evoked potential (Dimitrijevic et al. 1996, Golaszewski et al.1999, Tarkka et al. 2000, Tarkka and Pitkänen 2001).

Functional recovery without extensive structural reconstruction may be obtained by intensive training that optimises the use of spared neuronal structures (Wolpaw and Tennissen 2001). Use-dependent functional recovery and the concomitant reorganisation of the cortical representations after CNS injury do occur in both animal models and human patients, even in elderly adults in the chronic phase of stroke triggered by mesh-glove ES (Tarkka and Pitkänen 2001, Peurala et al. 2002).

11. SUMMARY AND CONCLUSION

The essential result of the SPR study was that the motor development which had ceased in the operated group resumed after operation. After five year follow-up there was no longer any significant difference between the groups. When this result is judged against the background of the other SPR studies the conclusion is that SPR is justified in highly selected cases.

Children with CP have difficulties selectively to activate muscles in part due to a lack of syncronisation of muscles. There is general consensus that NMES appears to give sensory feedback from limbs by activating spinal and supraspinal tracts and cortical body scheme areas which are needed to produce voluntary movement. The ability to move their limbs in turn motivates and increases the activity of the children during the therapy sessions. It is theoretically possible that sensory level stimulation may help co-ordination by re-establishing normal patterns of sensory and neuromuscular drive to spinal and supraspinal centres.

Concerning sensory level ES in the lower limb the essential result was that almost all children developed new active movements which persisted and even became stronger during the follow-up period after the intervention. The effect appears to be specific for ES and distinguishes it timely from a number of other therapies.

Sensory level ES in the upper limb showed that supporting time to the affected upper limb in crawling position at least doubled after the stimulation period. In addition active supination was

easier in the younger children. This most probably was due to their normal ROM. In the older children the supination was limited with the elbow extended. All children improved their dorsiflexion by at least one level in the Zancolli classification. The GAS scale revealed marked improvement of support time in the affected hand.

The present study showed that MENS therapy as an add-on procedure gives at least temporary relief to the myocontracture of the Achilles tendon in children with CP. An increase in ROM of this kind could at least postpone the operative elongation of the Achilles tendon for years.

The overall conclusion based on the present set of studies is that there most probably is a place for ES in the treatment of CP. The optimal timing, the best way of administration and positioning among the therapeutic modalities available for cerebral palsy awaits further studies.

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